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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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A calculated procedure will be developed by which the water can be followed as it travels downstream. This is actual water routing in contrast to the classical "water routing methods" which follow the hydrograph wave downstream. The procedure is expanded to include the tracing of conservative water chemistry as the water moves downstream. Thus, at a downstream station, it is possible to predict the conservative water quality parameters and compare these parameters with measured data if available. Good comparisons between calculated and measured conservative substances such as chlorides and conductivity indicate the calculational procedure is reasonably accurate. A further check on accuracy is obtained by performing a mass balance on the total water volumes involved. Predicted concentrations of substances such as total phosphorus and suspended solids do not compare well with the measured values, indicating that these are not conservative and that possible deposition and resuspension occur in various stream reaches during the storm. Furthermore, the methodology permits the estimation of the fractions of various parameters at a given downstream station which have been derived from various upstream sources. For example, the fraction of chloride passing the Fremont station on the Sandusky River which was derived from the Honey Creek basin can be calculated. Thus, if chloride reduction were desired for Lake Erie, the principal upstream sources can be identified by the methodology presented herein.

MATERIAL TRANSPORT IN RIVER SYSTEMS
DURING STORM EVENTS BY WATER ROUTING.

Final
technical rept.,

by

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March 1979

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ABSTRACT

Flow and water quality data (starting in 1976) have been collected, analyzed, and plotted at nine USGS gaging stations in the Sandusky River of northern Ohio for several storm events. A procedure has been developed whereby the water as it travels downstream is followed. The calculational procedure is further expanded to include the tracing of conservative water chemistry as it moves downstream. Thus, at a downstream station it is possible to predict such water quality parameters and compare them with their measured values. The conservative substances such as chlorides and conductivity compared well-- indicating that the calculations were reasonably accurate. Such substances as total phosphorus and suspended solids do not compare well indicating these are not conservative and that deposition and resuspension occur in various reaches of the stream. Further, the methodology permits the estimation of the fractions of these substances at a given downstream station which are derived from various upstream sources. Various factors such as point sources, river flow rate, etc. are discussed as to how they affect the transport of total phosphorus, suspended solids, chlorides, conductivity, the nitrogen species, and other water quality parameters.

INTRODUCTION

In order for planners and engineers to be able to analyze and evaluate instream conditions and recommend water quality management programs, a question might arise as to from what part of a watershed the major amount of a nutrient or flow originates. What is needed is a simple calculational procedure requiring a minimal amount of field data. The object of this report is to present such a procedure developed around the small amount of data available.

A calculational procedure will be developed by which the water can be followed as it travels downstream. This is actual water routing in contrast to the classical "water routing methods" which follow the hydrograph wave downstream. The procedure is expanded to include the tracing of conservative water chemistry as the water moves downstream. Thus, at a downstream station, it is possible to predict the conservative water quality parameters and compare these parameters with measured data if available. Good comparisons between calculated and measured conservative substances such as chlorides and conductivity indicate the calculational procedure is reasonably accurate. A further check on accuracy is obtained by performing a mass balance on the total water volumes involved. Predicted concentrations of substances such as total phosphorus and suspended solids do not compare well with the measured values, indicating that these are not conservative and that possible deposition and resuspension occur in various stream reaches during the storm. Furthermore, the methodology permits the estimation of the fractions of various parameters at a given downstream station which have been derived from various upstream sources. For example, the fraction of chloride passing the Fremont station on the Sandusky River which was derived from the Honey Creek basin can be calculated. Thus if chloride reduction were desired for Lake Erie the principle upstream sources can be identified by the methodology presented herein.

CALCULATIONAL PROCEDURE DEVELOPMENT

Water Mass Balance

Consider the mass balance for stream flow Q for an infinitesimal stream element x between large point sources such as tributaries. The rate of change in flow for the element is equal to the inputs minus outputs. The inputs consist of additions from small point and diffuse sources along x, the upstream flow, and ground water inflow. Outputs consist of stream outflow from the element plus losses to the stream bank. Gains or losses through ground water and stream banks will be assumed to be negligible. In reality, they should be minor during storm events. Also, they are extremely hard to approximate. The differential equation takes the form

$$\frac{\partial A \Delta x}{\partial t} = q \Delta x + Q - (Q + \frac{\partial Q}{\partial x} \Delta x) \quad \ldots Eq(1)$$

1

FLOW IN CFS (y-axis)
FLOW AREA IN SQ. FT. (x-axis)

FLOW VELOCITY = Q/A

WAVE VELOCITY

2

Figure 1
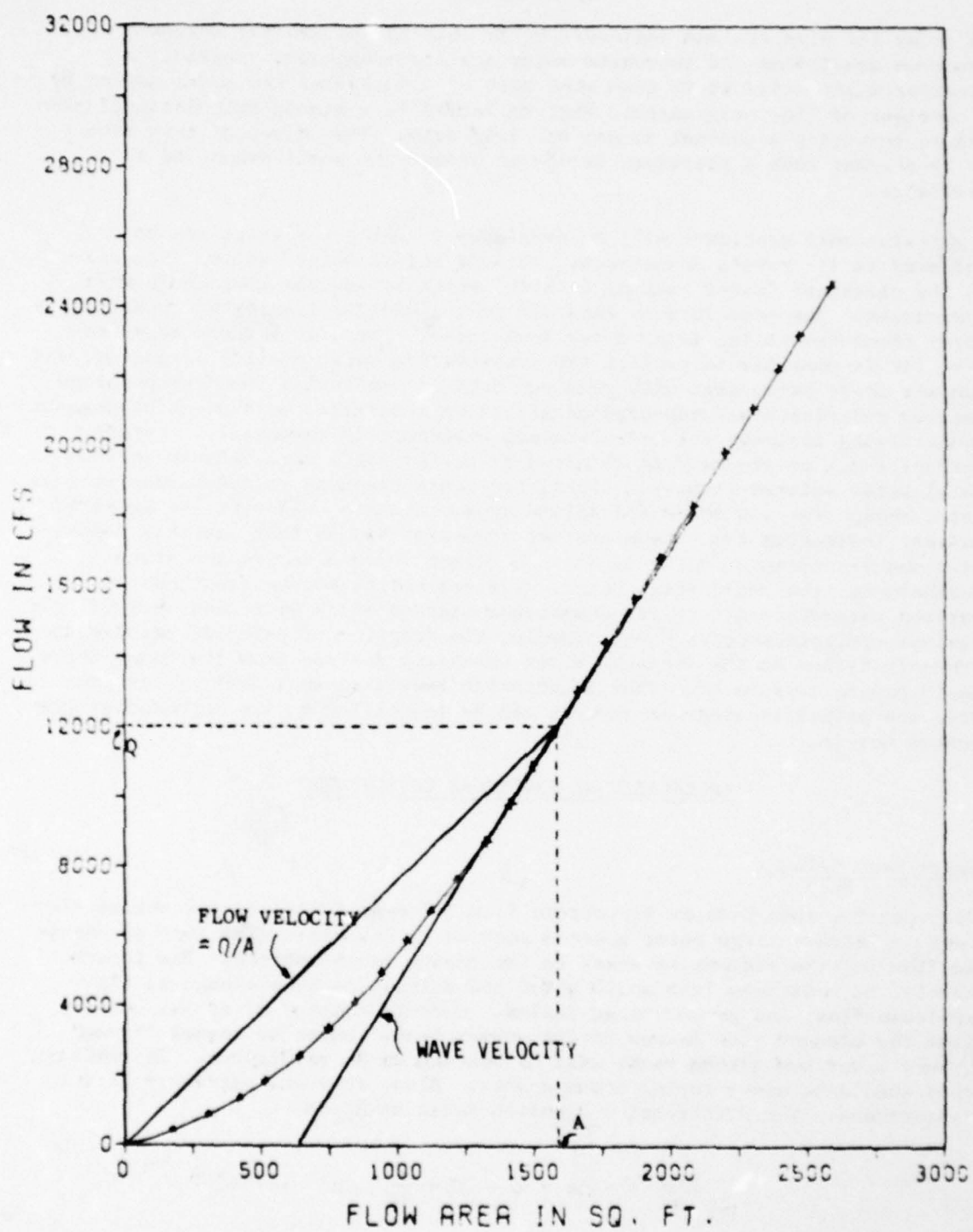
where A = stream cross sectional flow area
Q = discharge
t = time
x = distance downstream
Δx = incremental distance
q = diffuse lateral inflows per unit length

Point sources basically represent discontinuities in the river system and may be handled in two different ways if a numerical solution technique is used. First, point sources could be added in during the solution procedure by assuming that any which occur over an infinitesimal reach Δx can be distributed over the reach or secondly, the Δx's could be chosen such that the point sources are added to the stream at the end of a calculational step, meaning the flow at the end of one reach is updated for the beginning of the next reach.

Combining terms in Equation 1 and taking the limit as $\Delta x \rightarrow 0$ gives

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad \qquad ...Eq(2)$$

This is the standard differential equation used as a basis for all water (hydrograph) routing. Since this equation has two unknown parameters Q and A, a relationship known as the area-discharge curve is used to relate the two. In other instances a deterministic force balance is employed.

$$Q = f(A) \qquad \qquad ...Eq(3)$$

This relationship is either in the form of Equation 3 as determined from actual field data or as an empirical relationship such as

$$Q = \alpha A^n \qquad \qquad ...Eq(4)$$

where α and n must be approximated.

Both Equation 3 and 4 have been used with Equation 2 for water routing. Verhoff and Melfi (1978) and Verhoff, Melfi, and Yaksich (1979) have used field data while Huang (1978) uses an emperical relationship.

Figure 1 illustrates a typical curve for discharge versus wetted area for subcritical flow. This curve is typical for most streams. The average water velocity for a flow Q is Q/A and is shown on the diagram as the slope of a chord connecting a point Q on the curve and zero. The average hydrograph velocity is the slope of the line tangent to the curve at point Q. As can be seen from the curve, the hydrograph velocity is always greater than the water velocity. As the water moves downstream, the hydrograph will catch up to the
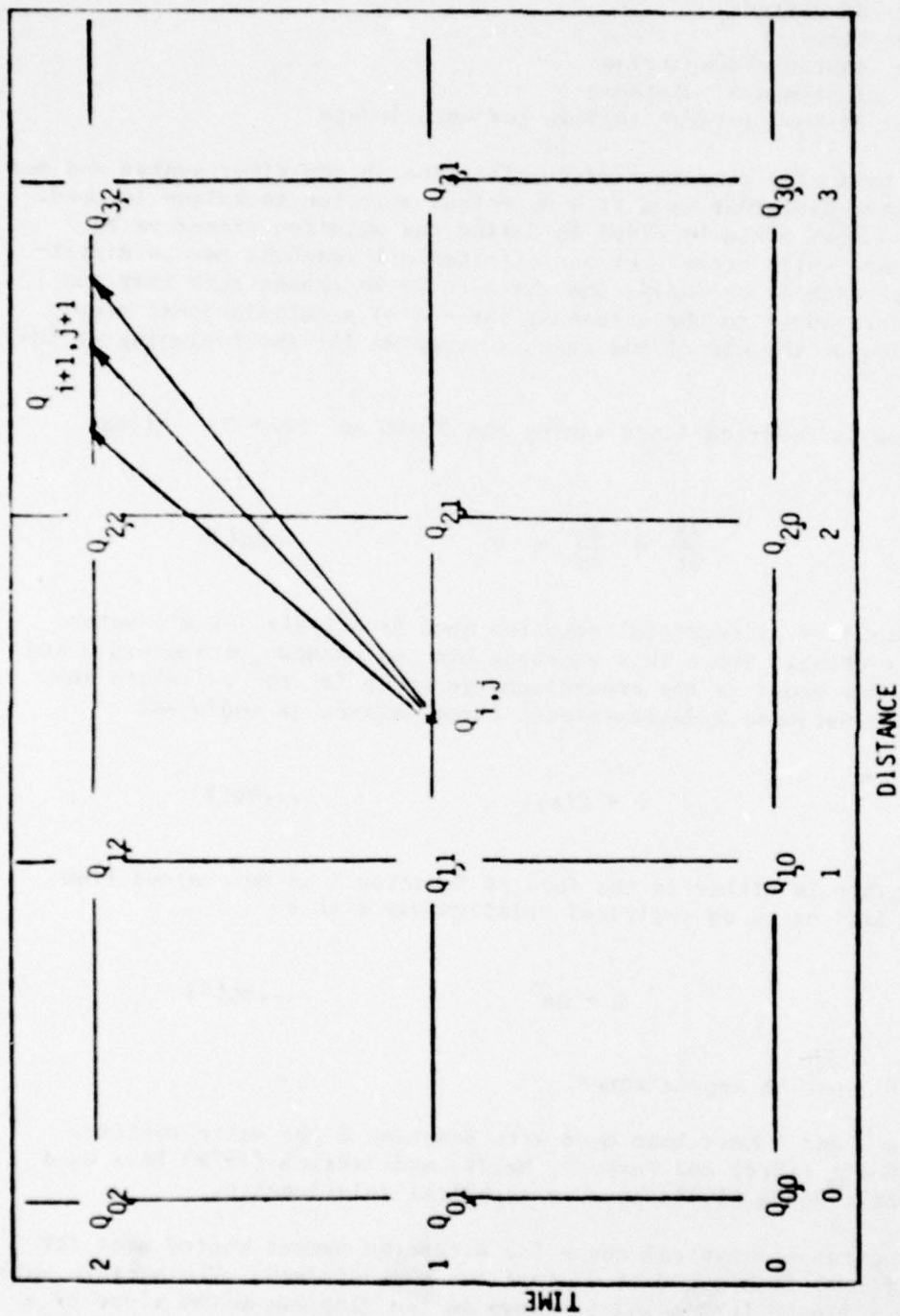
3

Figure 2

water, carry it a distance downstream, and then leave it behind. If a reference point is attached to the hydrograph, the water would be observed to move from left to right through the hydrograph.

Equations 2 and 3 or 4 can now be solved for one of the two parameters assuming the diffuse lateral inflows per unit length, q, is known or can be reasonably approximated. Depending upon the information wanted, two different approaches may be taken. If q is either known or can be reasonably approximated, Equations 2 and 3 can be solved using a finite difference scheme giving A or Q as a function of x and t. Such a solution would take the form in Figure 2. Figure 2 illustrates a solution matrix for flow for distance downstream from an upstream station and time into a storm event. Each nodal point which is indicated by Q represents a solution to Equation 2 for equal steps in distance and time. Tributaries that occur along the reach must be added in as discontinuity jumps. The values of Q at time zero for all distance are the boundary conditions while Q's for distance zero for all time are the initial conditions. Values other than those calculated for equal distance and time steps must be interpolated from these solutions. In this case, a relationship for the area-discharge curve would be needed at each x distance downstream. For all practical purposes, this relationship could be approximated from the relationship at end points of the stream reach of interest.

Hydrograph and Unmeasured Inflow Calculation

If information is just needed at the end points, an alternative approach could be taken by integrating Equation 2 over the total reach distance giving

$$\int_{L_1}^{L_2} \left\{ \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q \right\} dx \qquad \ldots Eq(5)$$

where L_1 is the upstream station distance
L_2 is the downstream station distance

This gives

$$Q_2 - Q_1 + \frac{\partial}{\partial t} \int_{L_1}^{L_2} A dx = \int_{L_1}^{L_2} q dx \qquad \ldots Eq(6)$$

where Q, A, and q are functions of time.

This equation is very similar to the "classic" routing techniques which state: the change in storage is equal to the input minus output. The integral of area is the storage between stations 1 and 2 and the integral on the right-hand side is the nonpoint inflow for the section. The stations of

DISCHARGE OR CROSS-SECTIONAL
FLOW AREA

STATION 1

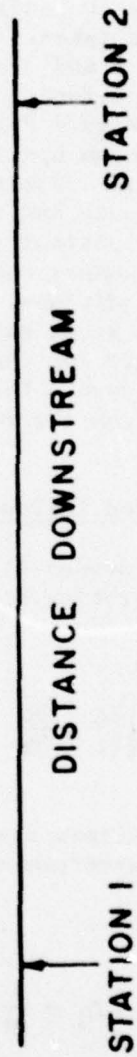STATION 2

DISTANCE DOWNSTREAM

Figure 3

interest are chosen relatively close together such that the discharge and/or flow area is approximately linearly dependent upon distance between the stations during storms as shown in Figure 3. Here the amplitude of discharge (or area) and variations are small relative to the wave length of the hydrograph wave form passing through the system. As a guide the stations are chosen such that the distance between them is much smaller than the hydrograph wave length, so for calculational purposes the water surface profile (area) is assumed to be relatively linear between stations as the wave progresses downstream as shown in Figure 3 by the heavy straight line. This is only true if there is no abrupt change in the area-discharge characteristics. This excludes the possible interruption in the surface profile due to large point source inflows such as major tributaries. At periods where the hydrograph is starting to rise from some base flow or where it peaks relatively sharply, this approximation may give some error.

Assuming a linear approximation in area can be used, Equation 6 gives

$$Q_2 - Q_1 + \frac{L\partial}{2\partial_t}(A_1 + A_2) = M \qquad \ldots Eq(7)$$

where M replaces the nonpoint integral and L is the distance between stations (L_2-L_1). At this point the term, M, could also include any large point sources along the reach such as tributaries. Thus, at appropriate times, M replaces all the point and diffuse source inputs between the two stations with a reach distance L. This equation may be used to calculated M between the stations. It should be noted that Equation 7 only has to be applied at the two end points of the reach. This equation can now be written in explicit finite difference form and solved for the local inflow (including or excluding point sources) between two stations using the measured hydrographs and Equation 3 or 4 at the two end stations. Equation 3 may be easier to use than Equation 4, since this relationship is actually obtained from field data. This is especially true since hydrographs are needed and area-discharge data are usually obtained in the process of defining the hydrographs.

It must be remembered that M is a calculated unmeasured inflow dependent upon Equations 7 and 3. In reality M might not exactly identify with the actual unmeasured flow if it could be determined independent of any routing.

Equation 7 may be rearranged to define a downstream flow Q_2 giving

$$Q_2 = f(A_2) = Q_1 - \frac{L\partial}{2\partial_t}(A_1 + A_2) + M \qquad \ldots Eq(8)$$

This equation may be used to "route" a hydrograph from an upstream station to a station downstream if the upstream hydrograph is known along with the area-discharge curves and the inflow function $M(t)$. Thus the only unknown is A_2 which can be found. Q_2 can be determined from A_2 by the area-discharge relationship.

A numerical technique can be used to solve Equations 7 and 8. For example, in explicit finite difference from Equation 8 takes the form

$$A_{2,j+1} = A_{1,j} - A_{1,j+1} + A_{2,j} +$$

$$\frac{2\Delta t}{L}(Q_{1,j} - Q_{2,j} + M_{j+1}) \quad ...Eq(9)$$

where 1 denotes the upstream station, 2 the downstream station, and j time. Note the solution is in terms of area. Areas must then be converted to flow through the use of the area-discharge curve.

$Q_{2,j}$ is the discharge at the downstream station at time j. This value is obtained from $A_{2,j}$ using the area-discharge relationships. The value of $A_{2,j}$ was determined by the above equation for the previous time step. Initially $A_{2,j}$ or $Q_{2,j}$ must be known as time equals zero.

If flow and consequently the flow area are known as the upstream and downstream station and the ungaged lateral inflow, M, is known, Equation 9 can be rearranged to solve for M giving

$$M_{j+1} = Q_{1,j} - Q_{2,j} +$$

$$\frac{L}{2\Delta t}(A_{2,j+1} - A_{2,j} + A_{1,j+1} - A_{1,j}) \quad ...Eq(10)$$

A quadratic approximation to the area as a function of distance in the integral which was linearized above has been attempted. This does not yield any simple formula or calculational procedure for estimation purposes.

Water Routing

The tracing of the water, and thus its chemistry as it moves downstream, can be derived from its average water velocity. If the velocity is known for all times during the storm, the water's position is known. Thus, for a given water volume

$$\frac{ds}{dt} = Q/A = v_w \quad ...Eq(11)$$

where Q = average flow
A = wetted cross sectional flow area
s = axial position of a water volume
t = time
v_w = average water velocity

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If v_w is assumed constant over a small step in time and distance, Equation 11 in its approximation form can be used to give the position of the water parcel as it travels downstream. Thus

$$\Delta s = v_w \Delta t \qquad \ldots Eq(12)$$

Once the position of the water is known as it travels downstream, the chemistry then can be computed.

Stream Chemistry Mass Balance

The one dimensional longitudinal mass balance for chemistry for a differential element gives

$$\frac{\partial C}{\partial t} + v_w \frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(D \frac{\partial C}{\partial x}\right) + S_{ource} + S_{ink} \qquad \ldots Eq(13)$$
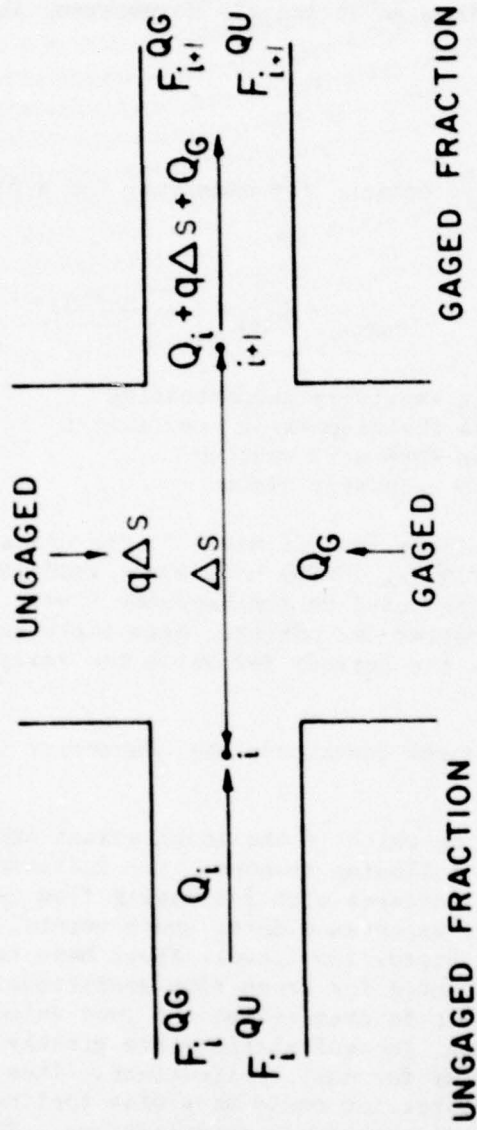
where C   indicates chemistry concentration
D   indicates the dispersion coefficient
S_{ource} indicates chemistry sources
S_{ink} indicates chemistry sinks

The above equation assumes the chemistry is well mixed in the cross section. Baker (1979) and Baker and Kramer (1979a, 1979b) have shown good mixing to have occurred at the sampling stations used on the Sandusky River. Generally the smaller the stream width, the better the mixing. Also there is better mixing during unsteady storm flows, the periods for which the analysis was developed.

By traveling with the water as it moves downstream the convective term $v_w \partial C / \partial x$ drops out.

The first term on the right hand side which is the longitudinal dispersion term is assumed negligible for the following reasons. The influence of dispersion relative to convection decreases with increasing flow rates. Although dispersion is of much less importance durng storm events, some researchers even neglect it during steady low flows. There have not been any dispersion coefficient studies conducted for storm flow conditions. This would indicate it may not be possible to even estimate a good value for storm flow. Also, by including dispersion, the calculations are greatly complicated. This might make them unwieldy for most applications. Thus a simple technique which does not include dispersion could have wide applicability by a variety of Government agencies and other study organizations. Finally the consequences of excluding the dispersion term can be tested by comparing the predicted versus measured results for conservative substances such as chlorides, and conductivity. Anticipating the results, it can be said the predictions without dispersion compare well with the measured values. Thus, it appears that the dispersion term can be neglected.

FLOW MASS BALANCE

UNGAGED

$q\Delta s$

Δs

Q_G GAGED

F_i^{QG} Q_i i $i+1$ $Q_i + q\Delta s + Q_G$ F_{i+1}^{QG}

F_i^{QU} F_{i+1}^{QU}

UNGAGED FRACTION

$$F_i^{QU} Q_i + q\Delta s = F_{i+1}^{QU}(Q_i + q\Delta s + Q_G)$$

$$F_{i+1}^{QU} = \frac{F_i^{QU} Q_i + q\Delta s}{Q_i + q\Delta s + Q_G}$$

GAGED FRACTION

$$F_i^{QG} Q_i + Q_G = F_{i+1}^{QG}(Q_i + q\Delta s + Q_G)$$

$$F_{i+1}^{QG} = \frac{F_i^{QG} Q_i + Q_G}{Q_i + q\Delta s + Q_G}$$

Figure 4

10

Because of the assumptions made, this procedure might not yield "accurate" results under conditions where dispersion is important. The "accuracy" is to be defined by the user from the results for conservative substances.

Thus Equation 13 becomes

$$\frac{\partial C}{\partial t} = S_{ource} + S_{ink} \qquad \ldots Eq(14)$$

This is essentially the Lagrangian form of the mass balance on the substance of interest.

This equation basically says that the substance concentration in a fixed volume of water will change because of internal generation, S_{ource} (e.g. nitrite generation by ammonia oxidation), or because of internal disappearance, S_{ink} (e.g. sediment settling to the bottom). Since this analysis was based on conservative substances both S_{ource} and S_{ink} are zero. Thus so long as there are no internal inputs for mixing the concentration remains constant as the water moves downstream. Since all external sources are assumed to occur at a point, no accumulation is possible. Only mixing need be considered at the point.

As an example, consider a steady state flow of A with concentration B. If another source is added with a flow of C and concentration D, the total flow is A+C with a resultant concentration of (AB+CD)/(A+C). The fraction of the mainstream flow is A/(A+C) and that of the added source is C/(A+C). The fraction of the chemistry (AB+CD)/(A+C) that originates from the mainstream flow is AB/(AB+CD), while that from the added source is CD/(AB+CD).

Flow Fractions

Following this same procedure, the flow fractions at time i+1 for the gaged and ungaged flow can be calculated as shown in Figure 4.

$$F_{i+1}^{QG} = \frac{F_i^{QG} Q_i}{Q_i + q\Delta s + Q_G} + $$

$$\frac{Q_G}{Q_i + q\Delta s + Q_G} \qquad \ldots Eq(15)$$

$$F_{i+1}^{QU} = \frac{F_i^{QU} Q_i}{Q_i + q\Delta s + Q_G} + $$

$$\frac{q\Delta s}{Q_i + q\Delta s + Q_G} \qquad \ldots Eq(16)$$

11

CHEMISTRY MASS BALANCE

$$F_i^{CU} Q_i C_i + C_u q \Delta s =$$

$$F_{i+1}^{CU} (Q_i C_i + C_u q \Delta s + C_G Q_G)$$

UNGAGED FRACTION

$$F_{i+1}^{CU} = \frac{F_i^{CU} Q_i C_i + C_u q \Delta s}{Q_i C_i + C_u q \Delta s + C_G Q_G}$$

$$F_i^{CG} Q_i C_i + C_G Q_G =$$

$$F_{i+1}^{CG} (Q_i C_i + C_u q \Delta s + C_G Q_G)$$

GAGED FRACTION

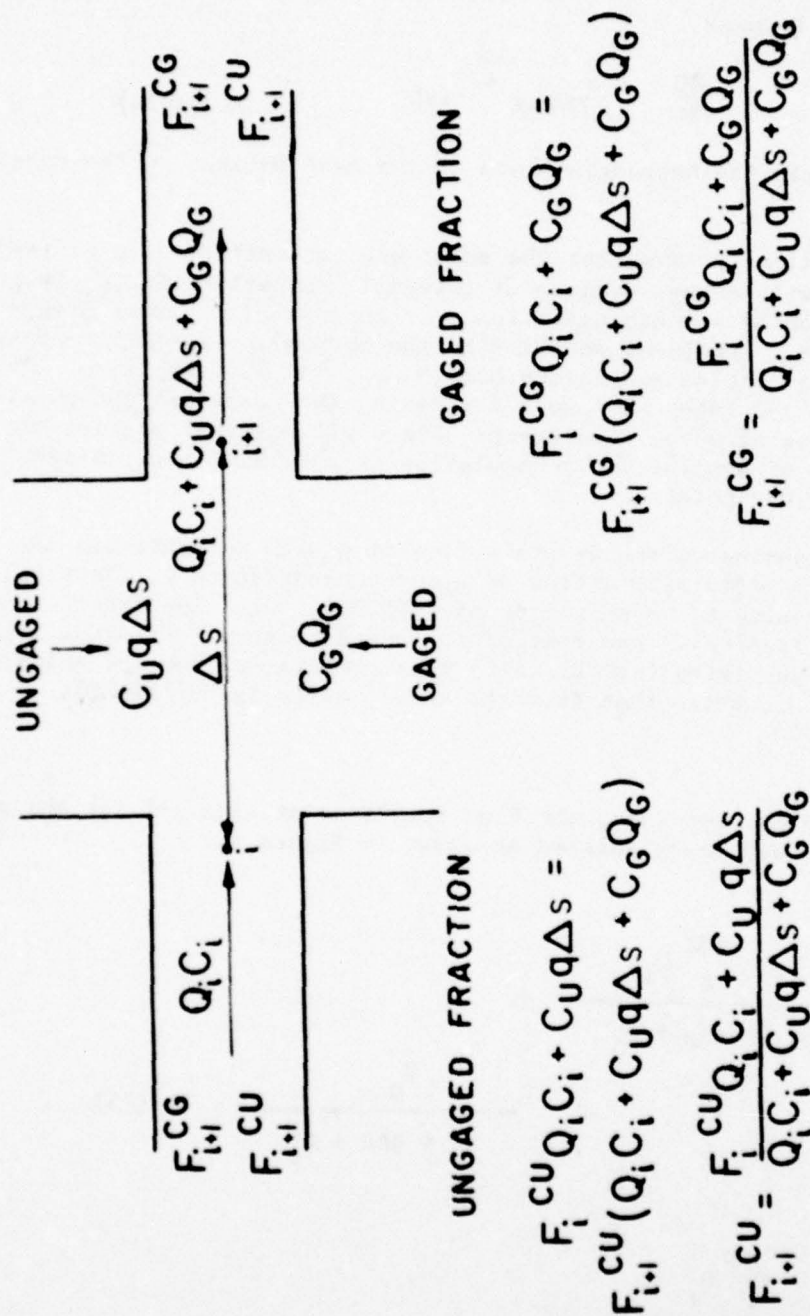$$F_{i+1}^{CG} = \frac{F_i^{CG} Q_i C_i + C_G Q_G}{Q_i C_i + C_u q \Delta s + C_G Q_G}$$

Figure 5

12

where F indicates fraction
G indicates gaged
U indicates ungaged (flow is
distributed as lateral inflow)
QG indicates gaged flow
QU indicates ungaged flow

Also the fraction of the flow from the upstream ith element at the i+1th point is

$$1 - F_{i+1}^{QG} - F_{i+1}^{QU} \ .$$

Water Chemistry Concentration

By doing a steady state mass balance on the chemistry, the chemistry concentration for the water at time i+1 can be shown to be

$$C_{i+1} = \frac{C_i Q_i}{Q_i + q\Delta s + Q_G} +$$

$$\frac{C_G Q_G}{Q_i + q\Delta s + Q_G} + \frac{C_U q\Delta s}{Q_i + q\Delta s + Q_G} \quad ...Eq(17)$$

where C indicates chemistry concentrations

On the right hand side, the first term represents the dilution of the upstream chemistry by the flow added from point (tributary) and nonpoint (ungaged lateral inflow) sources; the other two terms represent the addition by a tributary and unmeasured inflow for the incremental reach x, respectively. Knowing sufficient information on all the tributaries and each ungaged inflow area, the tributary and ungaged concentrations can be traced through the system.

Water Chemistry Fractions

The chemistry due to various inputs is not calculated directly, but is traced as a fraction of the concentration given in Equation 17. As shown in Figure 6 the gaged and ungaged chemistry fractions are given by

$$F_{i+1}^{CG} = \frac{F_i^{CG} Q_i C_i}{Q_i C_i + C_U q\Delta s + C_G Q_G} +$$

$$\frac{C_G Q_G}{Q_i C_i + C_U q\Delta s + C_G Q_G} \quad ...Eq(18)$$

13

$$F_{i+1}^{CU} = \frac{F_i^{CU} Q_i C_i}{Q_i C_i + C_U q \Delta s + C_G Q_G} +$$

$$\frac{C_U q \Delta s}{Q_i C_i + C_U q \Delta s + C_G Q_G} \qquad \ldots Eq(19)$$

where CG denotes gaged chemistry
CU denotes ungaged chemistry

Again the fraction the upstream station is $1 - F_{i+1}^{CG} - F_{i+1}^{CU}$.

The first term on the right-hand side represents the dilution of the chemistry fraction as the water travels downstream, while the last term is the fractional addition due to an ungaged source. Equations 15 and 18 may be repeated for several tributaries and other gaged point sources to be monitored. Tributaries which are not monitored are grouped with the nonpoint ungaged sources. These ungaged sources may be broken into as many subsources as desired by using Equations 16 and 19 as long as appropriate values for C and q for each subset exist or can be reasonably approximated.

Water to be traced starts out at the upstream station. Here it has the measured chemistry concentrations and flow at that station; and the fraction from the upstream station is one while all other fractions are zero. As this water travels downstream, the influence of the upstream station becomes less and less while the influence of the unmeasured contribution increases. When this water hits a tributary during a routing increment x, the tributary input affects the water at this point. Thereafter, the tributary fraction is diluted.

The calculations translate the chemistry and water to the downstream station where comparisons are made with measured parameters. The preceding derivations were made only for this comparison and they will not necessarily give accurate information between the stations of interest.

CALCULATIONAL PROCEDURE

The fundamental principles useful for understanding the transport of materials in streams have been discussed in the previous sections. The goal of this section is to present the sequence of calculations required to follow the nutrients and other materials as they move through the main stem of a river system. Basically these calculations are accomplished in two steps.

SANDUSKY RIVER FROM
BUCYRUS TO UPPER SANDUSKY
STORM BEGINNING 77/02/22
— CALCULATED LOCAL INFLOW
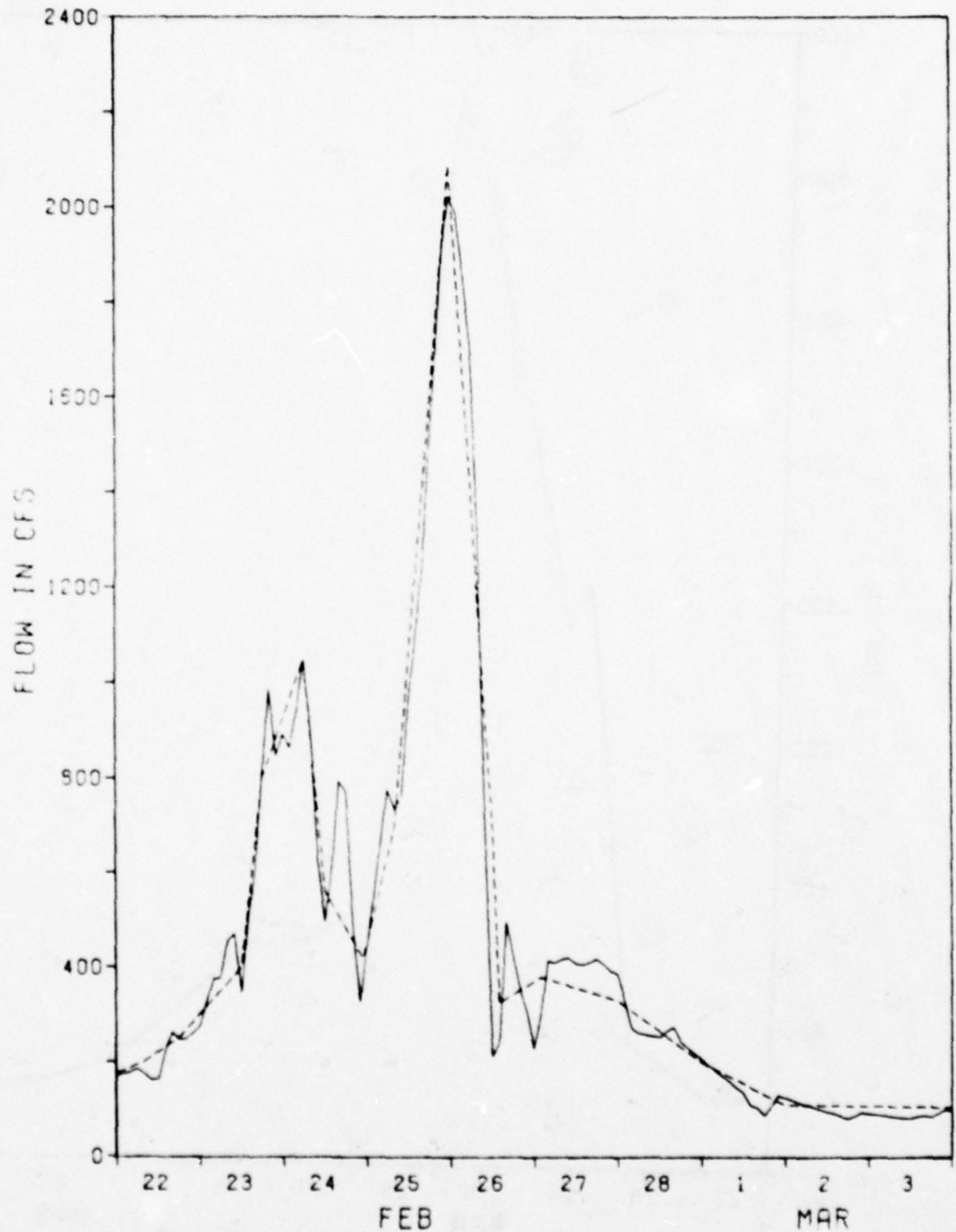--- APPROXIMATED LOCAL INFLOW
INCLUDING TRIBUTARIES

Figure 6

15

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22
— OBSERVED HYDROGRAPH
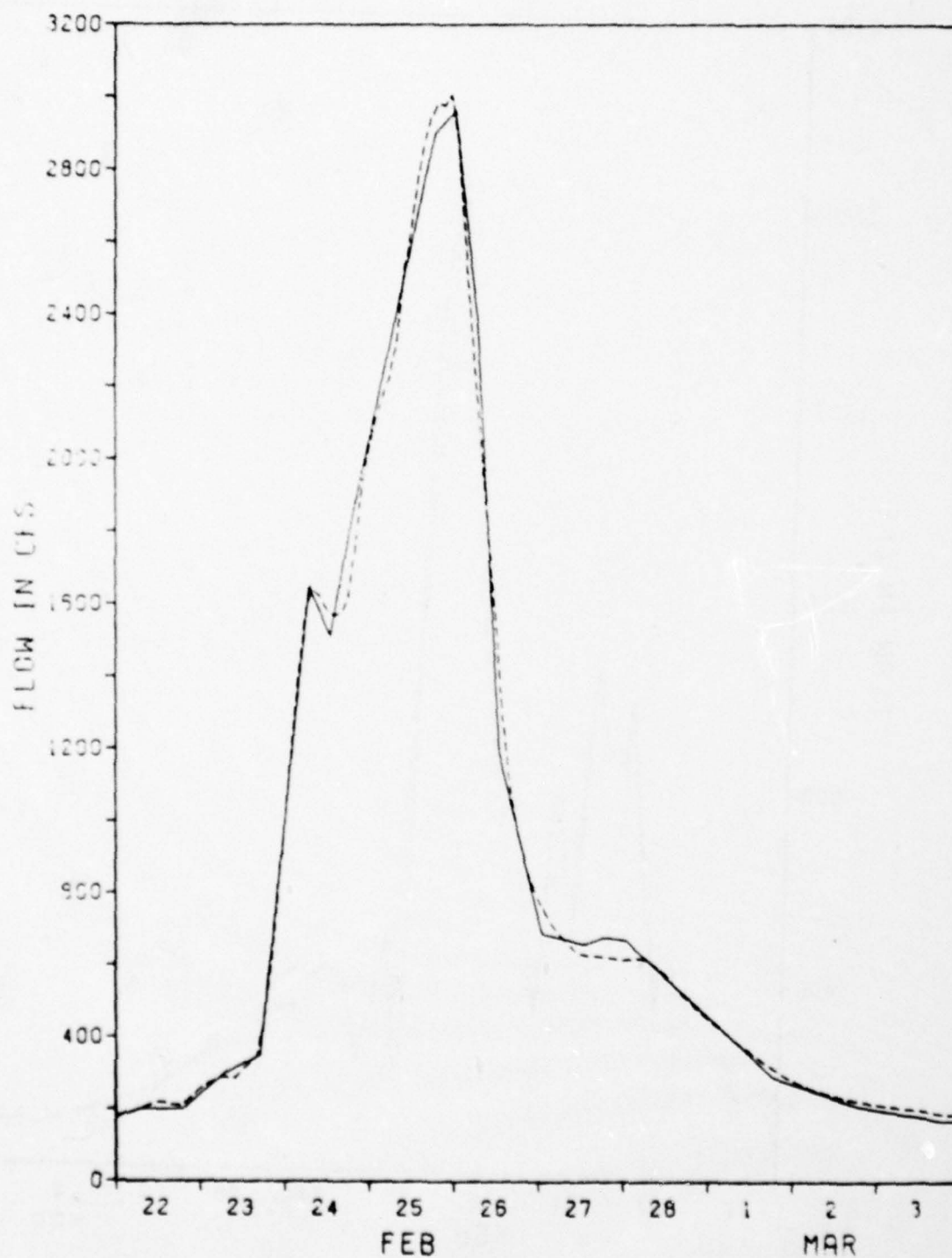--- CALCULATED HYDROGRAPH

Figure 7

16

First the movement of the water from the upstream station and the tributaries to the downstream station must be traced. Once this movement of the water is quantified the transport of nutrients can be calculated.

The calculations described herein trace the water and substances as they are transported from an upstream station of a river to a downstream station. In order to trace the water, some relationship between the discharge and the river cross-sectional area (area-discharge relationship) must be used. For exact calculations this discharge relationship should be measured as a function of distance downstream. However, for calculational purposes herein, it will be assumed that the area-discharge relationship at each point is an average of that at the upstream and downstream stations. Also, for calculations in the main stem of a river it is necessary to know for any tributary of interest its flow and material inputs at its mouth. However, the measuring stations on the tributaries are usually located some distance upstream. Therefore the tributary inputs must be translated downstream to the mouth before the main stem calculations can be completed.

Water Transport Calculations

Many procedures have been developed for the solution of Equation 2 including finite difference schemes and the method of characteristics. The major goal of these solution techniques has been to model and predict the height of the water (hydrograph wave) during a storm. The goal of the paper presented here is quite different and thus the manner in which this equation is used will be different. Since the water flow is known both at the upstream and the downstream stations, the main use of Equation 2 is for the calculation of the unmeasured lateral inflow, q. The equation is then used to predict the downstream hydrograph with smoothed values of the calculated inflow q.

The equation used to calculate M, the local inflow between the two main stem stations including tributaries, is given in Equation 10, where the length between stations is L and the time interval is $\triangle t$. Since the discharge Q and the cross-sectional area A are known as a function of time at both upstream and downstream stations (the area-discharge curve at each station is employed), the only unknown in this equation for any time interval is M_{j+1}. Thus the lateral inflow for that section of the river can be calculated as a function of time for the increments of time. Such a calculation between Bucyrus and Upper Sandusky, Ohio, on the Sandusky River is shown in Figure 6. The inflow functon is somewhat irregular and a smoothed version of this curve is also shown in this figure.

The smoothed inflow function M obtained from Figure 6 is used along with the upstream discharge and discharge area for a storm along with the past downstream discharge to predict the future downstream discharge area and discharge using Equation 9. The resulting predictions are shown in Figure 7. It can be seen that using the smoothed input functions causes little deviations in the downstream hydrograph.
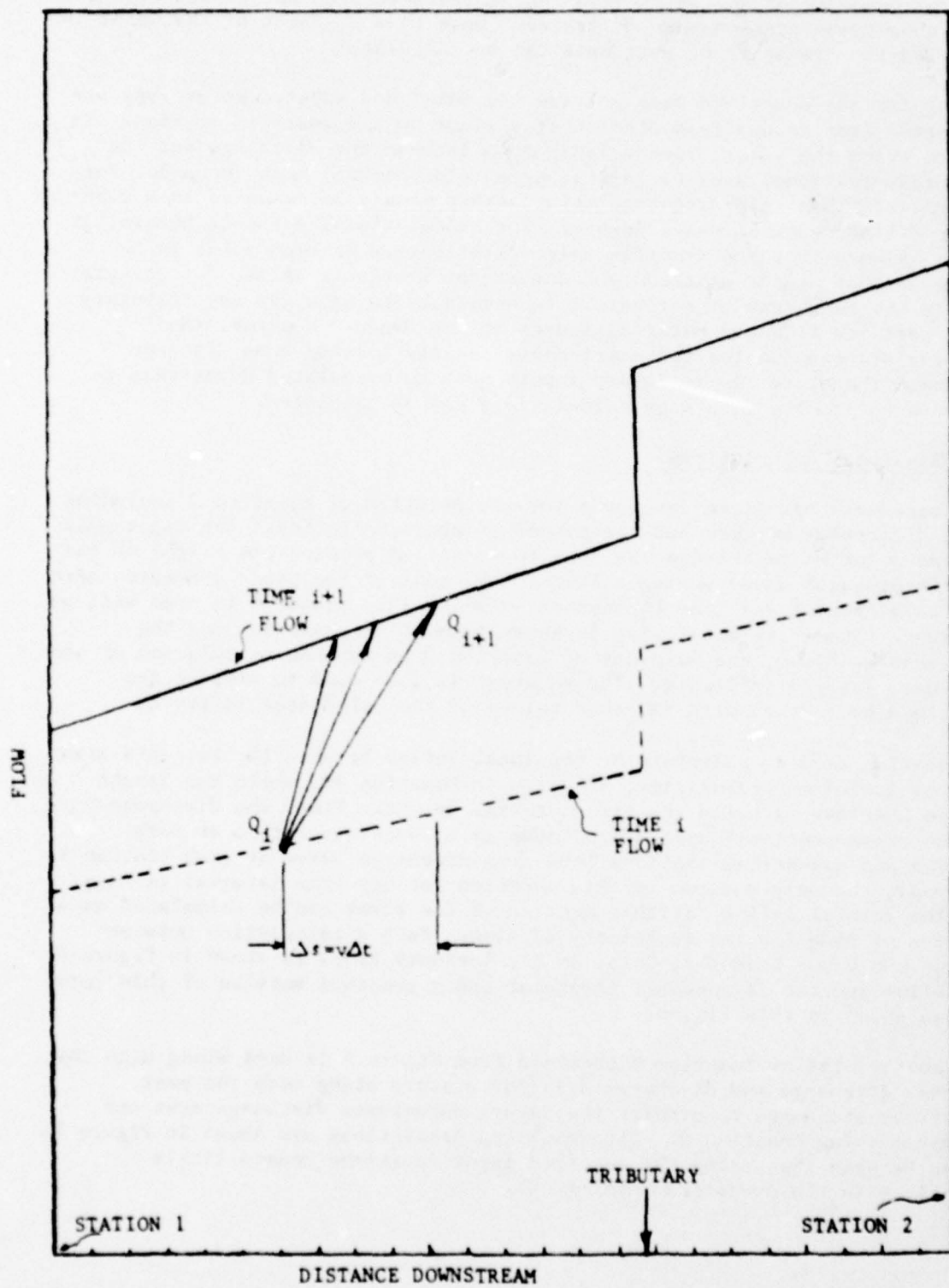
Figure 8

The calculated inflow function M contains both the measured tributary inflow and that resulting from unmeasured areas draining directly into the main stem of the river. The unmeasured inflow is calculated by subtracting the tributary inflow from the calculated total inflow. Occasionally, some calculated values of the net unmeasured inflow are negative. This could be realistic because there can be a significant recharge of the groundwater especially during the summer months in this area (western Ohio). However, since this occurs rarely and randomly during the calculational procedure, the unmeasured inflow was constrained to be equal to or greater than zero.

The tributary inflow which is subtracted from the total inflow is that evaluated at the tributary mouth. Since the measurement point on the tributary is some distance upstream from the mouth, it is necessary to calculate the inflow at the mouth. This is accomplished by using Equation 10 to calculate an M for the area upstream of the measurement point. The upstream station is taken as the uppermost headwaters of the stream with a zero area-discharge curve and hydrograph. This local inflow is then prorated by the area drained in the short distance from tributary measurement station to its mouth and used in Equation 9 to calculate the hydrograph at the tributary mouth.

In all the cases studied in the Sandusky River, the inflow from the measurement point to the tributary mouth was minor. The major change that occurred in translating the tributary flow from the measurement point to the mouth was the delay in time at which the flow entered the main stem of the river.

At this point the inflows to the main stem of the river are defined for the *entire storm event* and the water can be traced as it progresses downstream. The basic equation used to specify the position of the water is Equation 11 or its approximation Equation 12. Using a linear approximation for the flow between stations and using the known flows at the upstream and downstream stations as well as the known tributary inflows it is possible to predict the discharge in the main stem of the river as a function of distance for any instant in time. This is shown in Figure 8 for a time t_i and the next time increment $t + \Delta t$ which equals t_{i+1}. Given that the parcel is at a point s_i at time t_i with flow rate Q_i, we wish to calculate the position of the parcel at time t_{i+1}. From the area-discharge relationships at the end stations the cross-sectional area of the river at the point of interest is estimated and the water velocity is calculated as Q_i/A_i. During the time interval $t = t_{i+1} - t_i$ the water will move to a new position s_{i+1}. This position is calculated by the following formula.

$$s_{i+1} = s_i + (Q_i/A_i)\Delta t \qquad \qquad \ldots \text{Eq (20)}$$

This calculation then positions the water parcel at distance s_{i+1} and t_{i+1}. This point is indicated by Q_{i+1} on Figure 8. This process is then repeated with the flow as a function of distance drawn for time t_{i+2}.

STATION 2

STATION 1

TRIBUTARY

DISTANCE DOWNSTREAM
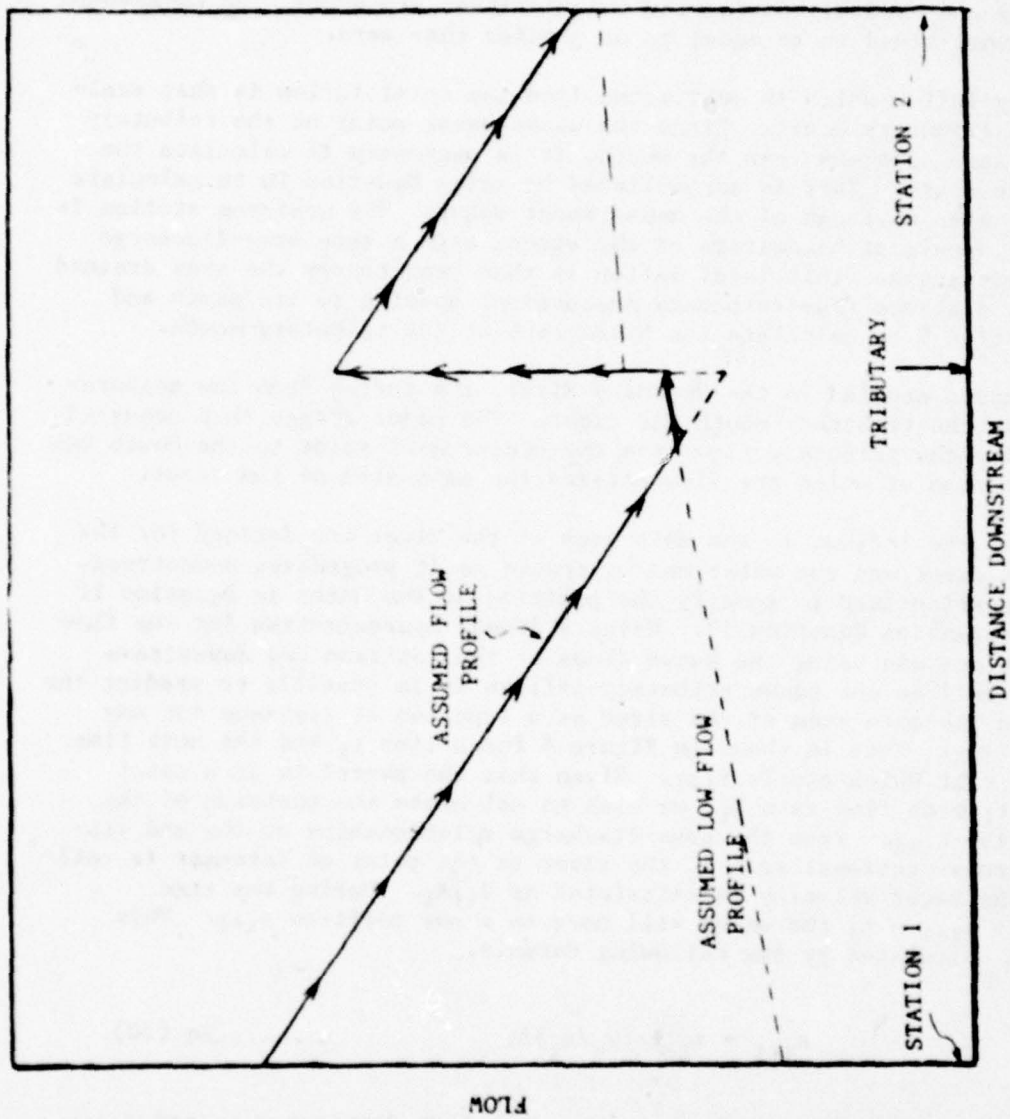
FLOW

ASSUMED FLOW PROFILE

ASSUMED LOW FLOW PROFILE

Figure 9

For greater accuracy, the following formula was used:

$$s_{i+1} = s_i + \{(Q_i/A_i + Q_{i+1}/A_{i+1})/2\}\Delta t \qquad \ldots \text{Eq.(21)}$$

This equation is used iteratively after a first estimate of s_{i+1} and Q_{i+1} is obtained from Figure 8 until the approximation for s_{i+1} and Q_{i+1} match with the flow curve at t_{i+1}. This is shown in Figure 8.

This calculation process is repeated in the same manner except when a tributary is crossed. If the calculation of the new position of the water, s_{i+1}, indicates that a tributary has been passed the calculation is modified such that the increment of time Δt is divided into two parts. The firt part carries the water to the tributary using the velocity calculated at the starting point. For the remainder of Δt, a distance of travel is calculated using the main stem stream flow just downstream of the tributary mouth as the starting point.

This calculation then permits the position of the water to be known as a function of time. Usually the water is started at the upstream station, $s = 0$, at different times. Some water is "tagged" as it starts downstream before the storm begins at the upstream station. Thereafter, water from different parts of the upstream hydrograph are chosen at time intervals such that the fate of the upstream water can be followed through the main stem of the stream. Thus it is now possible to predict when water from a position in the upstream hydrograph reaches the downstream station. Usually, the water travels slower than the storm wave (hydrograph) and hence, the water at the peak of the hydrograph at the upstream station reaches the downstream station after the hydrograph has peaked at this station.

In addition to computing the position of the water it is possible to determine the composition of the water which arrives at the downstream station. That is, the fraction of the water which resulted from the upstream station, the tributaries, and the unmeasured inputs can be found. The equations for these calculations were given as Equations 15 and 16. The fraction for each of the inputs is updated during each time increment, i.e. as time goes from t_i to t_{i+1}. Thus it would be possible to calculate the fractions of water from each source as a function of distance for the water.

Occasionally, during the calculations the discharge predicted from the linear curve between the two main stem stations including discontinuities caused by the tributary input will drop below that of the low flow discharge in the river. This is shown in Figure 9. In this instance the flow is smoothed along the low flow line as shown in Figure 9. This occurs rarely, but when it does occur it is during a rapidly rising or declining flow of a storm. The rapidly declining stage of the storm is shown in Figure 9. It should be noted that this aproximation does not introduce much more error since the linear approximation for the discharge as a function of distance is good during these rapid changes in flow.

Concentration Calculations

The concentration of the water at the upstream station is known from the data measured there. As the water leaves the upstream station it mixes with water from the unmeasured inflow areas of the basin and with the water from the tributaries. Since the concentration of materials in the unmeasured water or the tributaries is not necessarily the same as that of the water in the main stem of the stream, the concentration of material in the water changes as it proceeds downstream. Stated simply, the water in the main stem is diluted by water from tributaries and unmeasured areas of the basin.

If the storage capacity of the river at the point of external water entry is small compared to the flow rates of the water, the steady state mixing concept can be used to calculate the resulting concentration in the water. This assumption is very good for all streams which do not have large natural or man-made impoundments; this is the case for the Sandusky River which is studied herein. The steady state mixing equation was given as Equation 17.
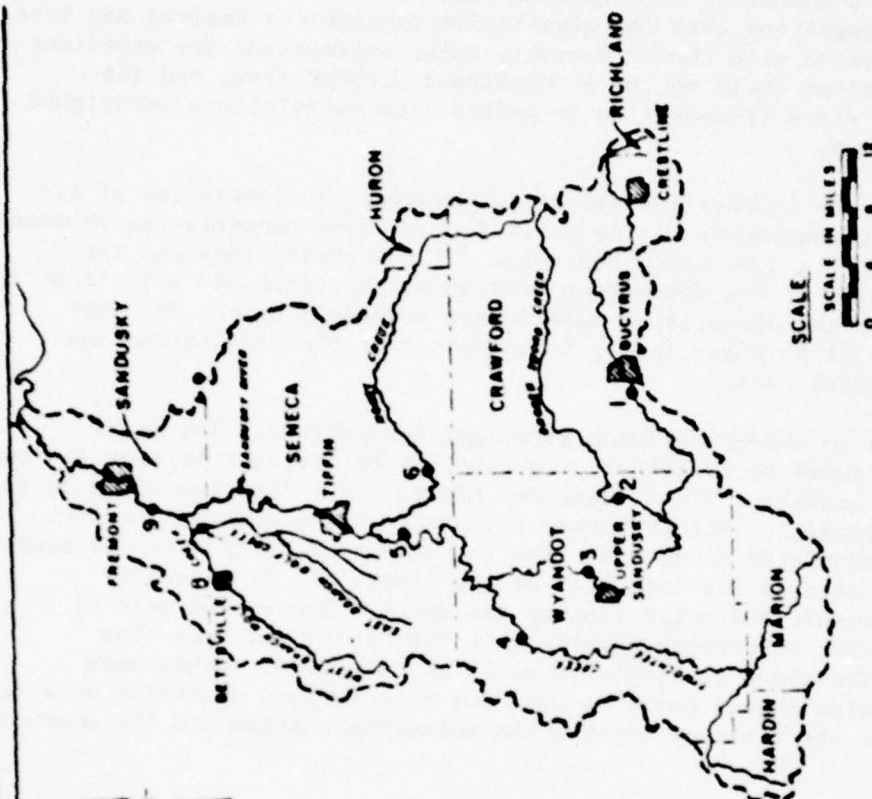
This equation is calculated for each increment in time and thus the concentration of the material of interest is determined as a function of distance since distance is also a function of time. It must be remembered that this calculation presumes the substance is conserved in the water.

This calculation, in particular, yields the predicted concentration at the downstream measurement station on the main stem. At this point the calculated concentration can be compared with the measured value. It is expected that conserved substances will compare favorably and that non-conserved substances will exhibit deviations from the predicted values. These deviations will give indications as to transport processes e.g. if the measured concentration is greater than that computed, there might have been some net resuspension of that substance for the stream bottom and banks into the flowing water. Thus, the comparison between calculated and measured concentration at the downstream station is valuable in that it permits a test of the accuracy of the computations for conservative substances such as chloride or conductivity and it yields information as to the transport processes of nonconservative substances such as suspended sediment and total phosphorus.

In addition to the computations on the concentration of the water as a function of distance, it is possible to calculate the fraction of the substance in the water which comes from different sources. These fractions, from the upstream station, from tributaries, and from unmeasured areas are calculated as the water proceeds downstream. The equations for these calculations were given as Equations 18 and 19.

It must be remembered that these calculations are for conservative substances such as chlorides or conductivity. However, the fractions of other substances can contain significant information as to the processing of these substances in the stream. For example, one might find a correlation between decreased quantities of a given substance e.g. total phosphorus and the time when a given fraction of total phosphorus was predicted to be from a given source, e.g. a particular tributary. Thus one might conclude that the total phosphorus from that source might be settling out in the main stem of the river.

SANDUSKY RIVER BASIN

N

HURON

SANDUSKY

RICHLAND

SENECA

FREMONT

TIFFIN

CRESTLINE

6

CRAWFORD

BETTSVILLE

8

9

BUCYRUS

WYANDOT

3

UPPER SANDUSKY

2

4

MARION

HARDIN

5

SCALE

SCALE IN MILES

0   4   8   12

LEGEND:
● INDICATES WATER QUALITY SAMPLING STATION

STATION IDENTIFICATION

1   Sandusky River near Bucyrus

2   Broken Sword Creek at Nevada

3   Sandusky River near Upper Sandusky

4   Tymochtee Creek at Crawford

5   Sandusky River near Marlco

6   Honey Creek at Melmore

7   East Branch Wolf Creek at Bettsville

8   West Branch Wolf Creek at Bettsville

9   Sandusky River near Fremont

Figure 10

23

Discussion of Errors

The computational technique presented herein for the tracing of substances in a river contains a number of expedient assumptions. These assumptions are made with the recognition that the quantiative conclusions derived may have some error associated with them. However, these assumptions are expedient i.e. the computations could not be accomplished without them, and the understanding of river transport to be gained from calculations outweighed the errors incurred.

The best test of the computation technique involves the comparison of the predictions and measurements of the water flow and the conservative substance concentrations at the downstream stations. If the predictions and the measured quantities at the downstream station match reasonably well it will be concluded that the assumptions made do not adversely effect the computations. As will be shown later, it appears that the predictions and measurements compare well.

It is worthwhile to summarize these expedient assumptions. The water discharge is presumed to be linear as a function of distance between the two main stem river stations. To presume any higher order function would be too complex mathematically. The tributary discharge and concentrations were approximately translated downstream from the measuring station to the mouth where the water entered the main stem of the river. It is generally impossible to measure the water flow at the mouth. The method used to translate the water downstream (basically a time delay and area flow augmentation) were about as simple as could be conceived. Other more sophisticated calculations could be used for this purpose depending upon the application i.e. the distance between the measuring station and the mouth of the tributary.

It is also assumed that the unmeasured inflow cannot become negative. This assumption is invoked infrequently. However, it may not necessarily be true since a negative inflow from unmeasured areas is possible when water from the river enters the soil for ground water recharge. Also, the flow in the stream is never permitted to drop below that of low flow conditions. Again this condition is involved infrequently. A higher degree approximation of the discharge as a function of distance might alleviate this problem.

CALCULATIONAL RESULTS

The calculational procedure developed above was used to study storms on the Sandusky River basin. Water routing was started at the USGS gaging station near Bucyrus with the calculated results being compared to measured data at downstream stations near Upper Sandusky, Mexico, and Fremont. A map of the watershed is shown in Figure 10.

These data were collected and analyzed by Heidelberg College, River Studies Laboratory, for the U. S. Army Corps of Engineers. See U.S. Army Corps of Engineers, Buffalo District (1978a, 1978b, 1978c). The area-discharge relationships were developed from actual field data collected by the USGS at the

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Table 1 - Ungaged Lateral Inflow Concentrations
Storm of 77/02/22

Station	Ungaged Lateral Inflow Concentrations Excluding Tributaries				
	TP mg/l	NO_2+NO_3 mg/l	SS mg/l	Cl mg/l	Cond. umhos
Bucyrus					
	0.2	3.0	40	25	650
Upper Sandusky					
	0.2	3.0	75	50	500
Mexico					
	0.2	2.0	40	50	500
Fremont					

SANDUSKY RIVER AT UPPER SANDUSKY
STORM BEGINNING 77/02/22
— OBSERVED HYDROGRAPH
--- CALCULATED HYDROGRAPH
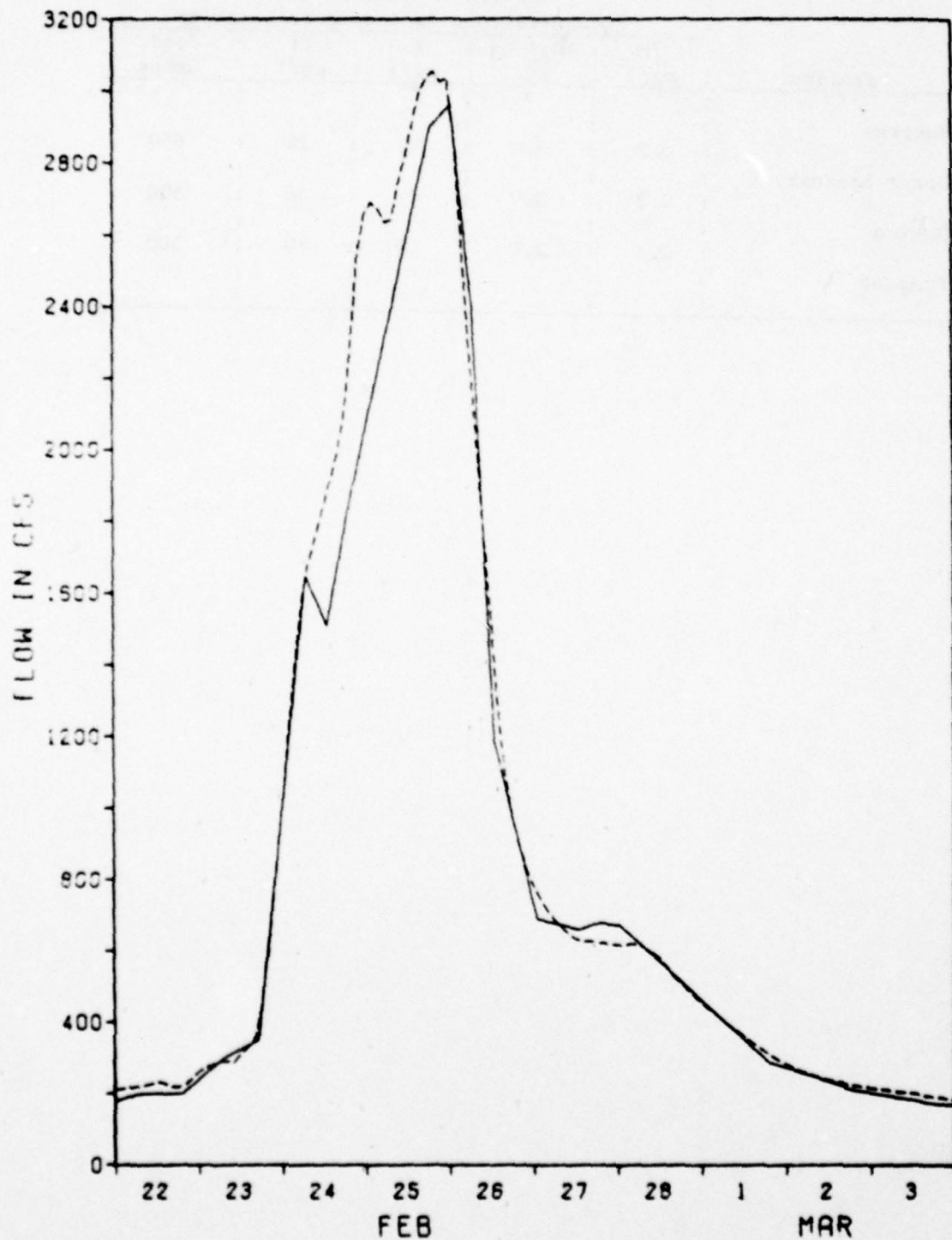
Figure 11

26

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22

Figure 12a

27
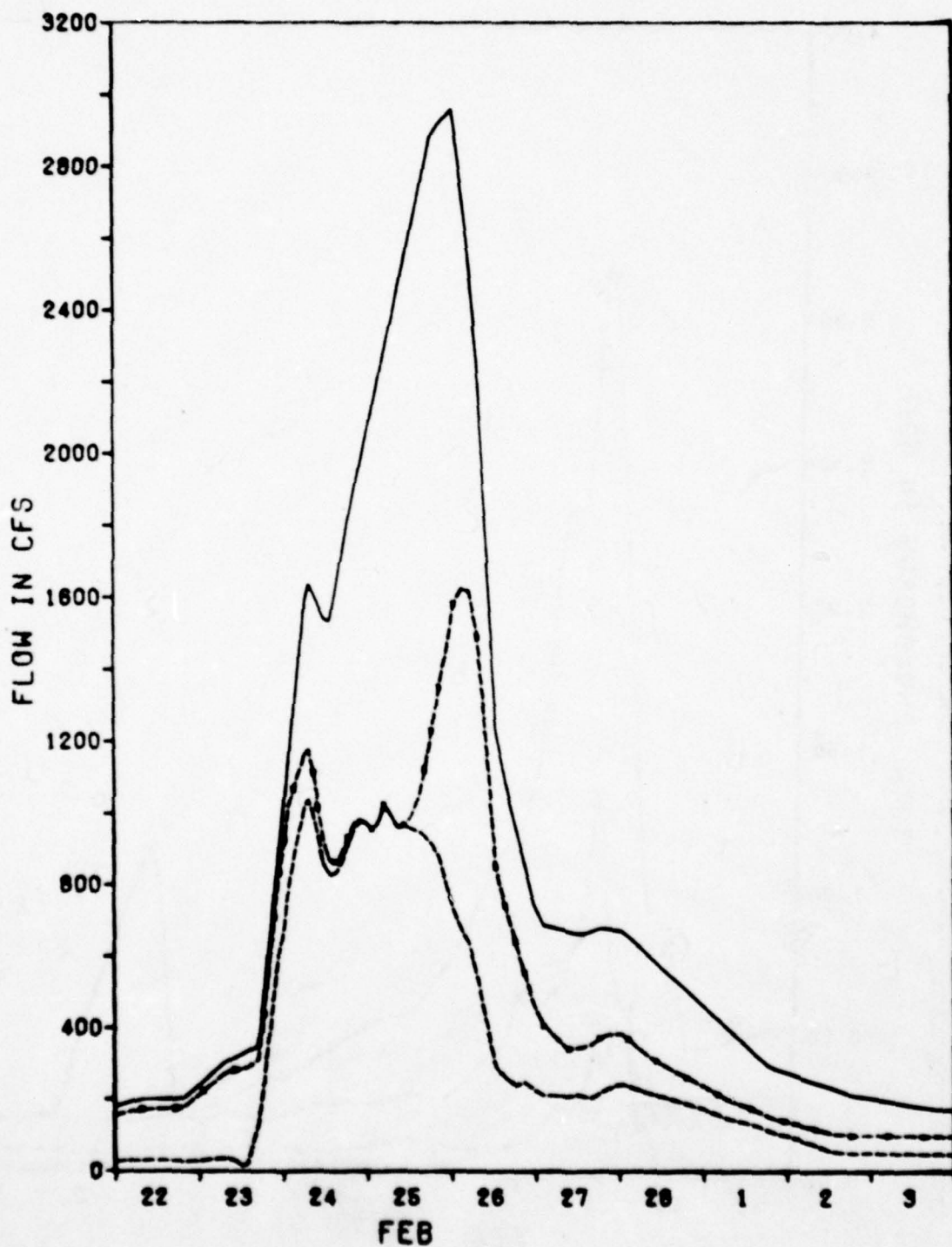
SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22
—— MEASURED   ══ UNMEASURED
●— CALCULATED   ── BUCYRUS
══ BROKEN SWORD CREEK ══ RESUSPENSION
══ DEPOSITION
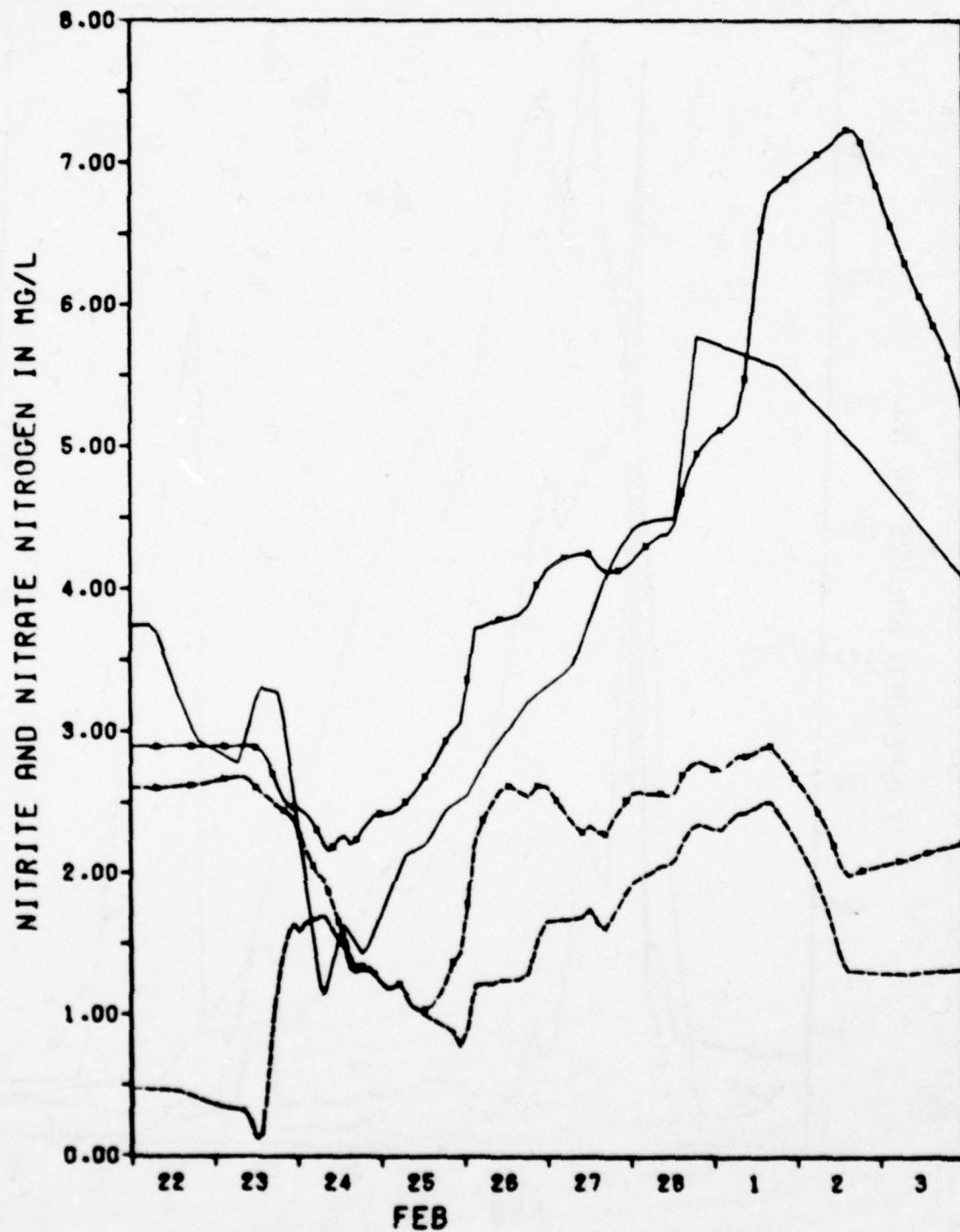
Figure 12b

28

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22

Figure 12c

29

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22
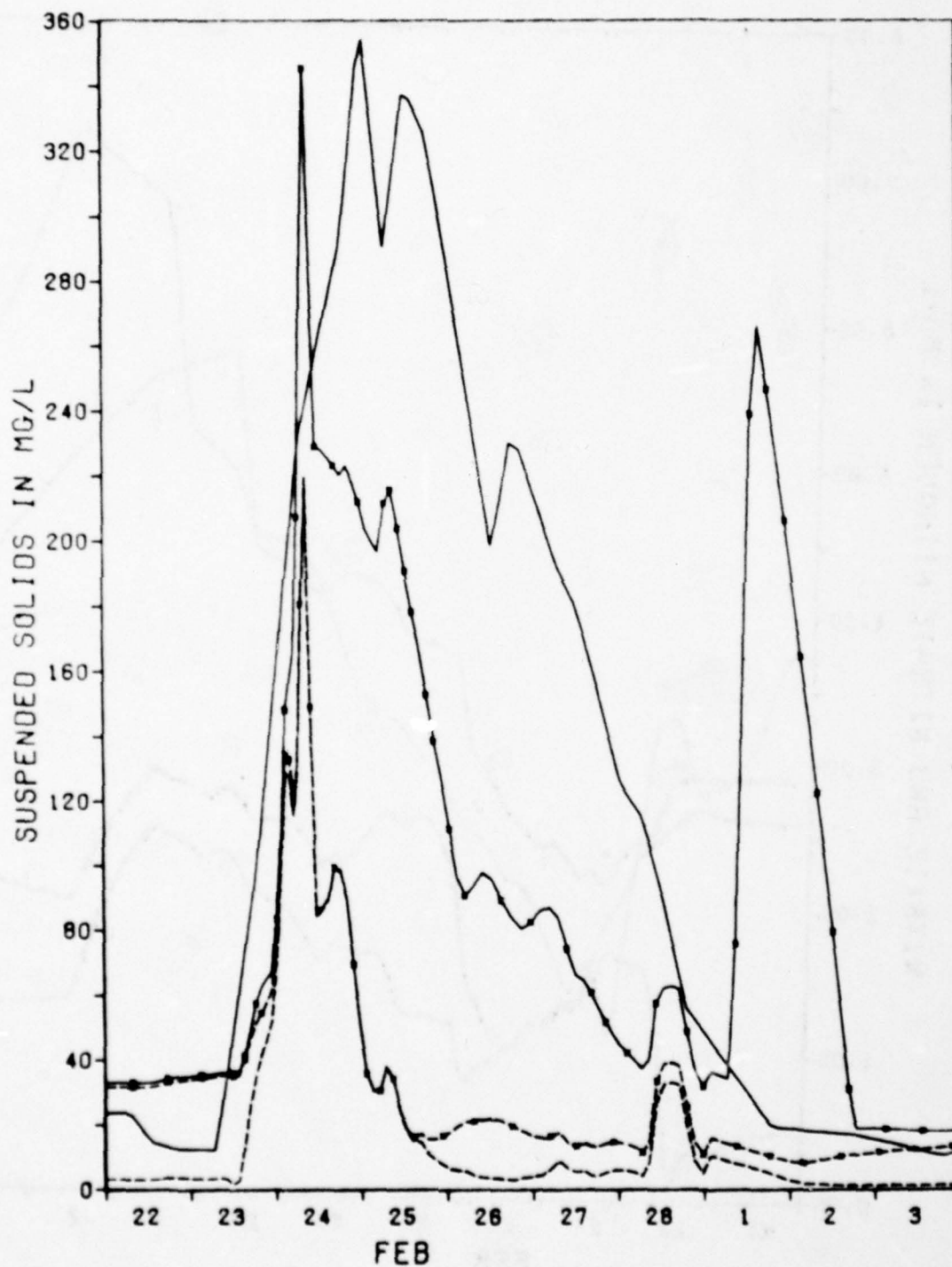
Figure 12d

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22

—— MEASURED   ☰☰☰ BROKEN SWORD CREEK
•—• CALCULATED   ☰☰☰ UNMEASURED
      ☰☰☰ BUCYRUS

Figure 12e

31
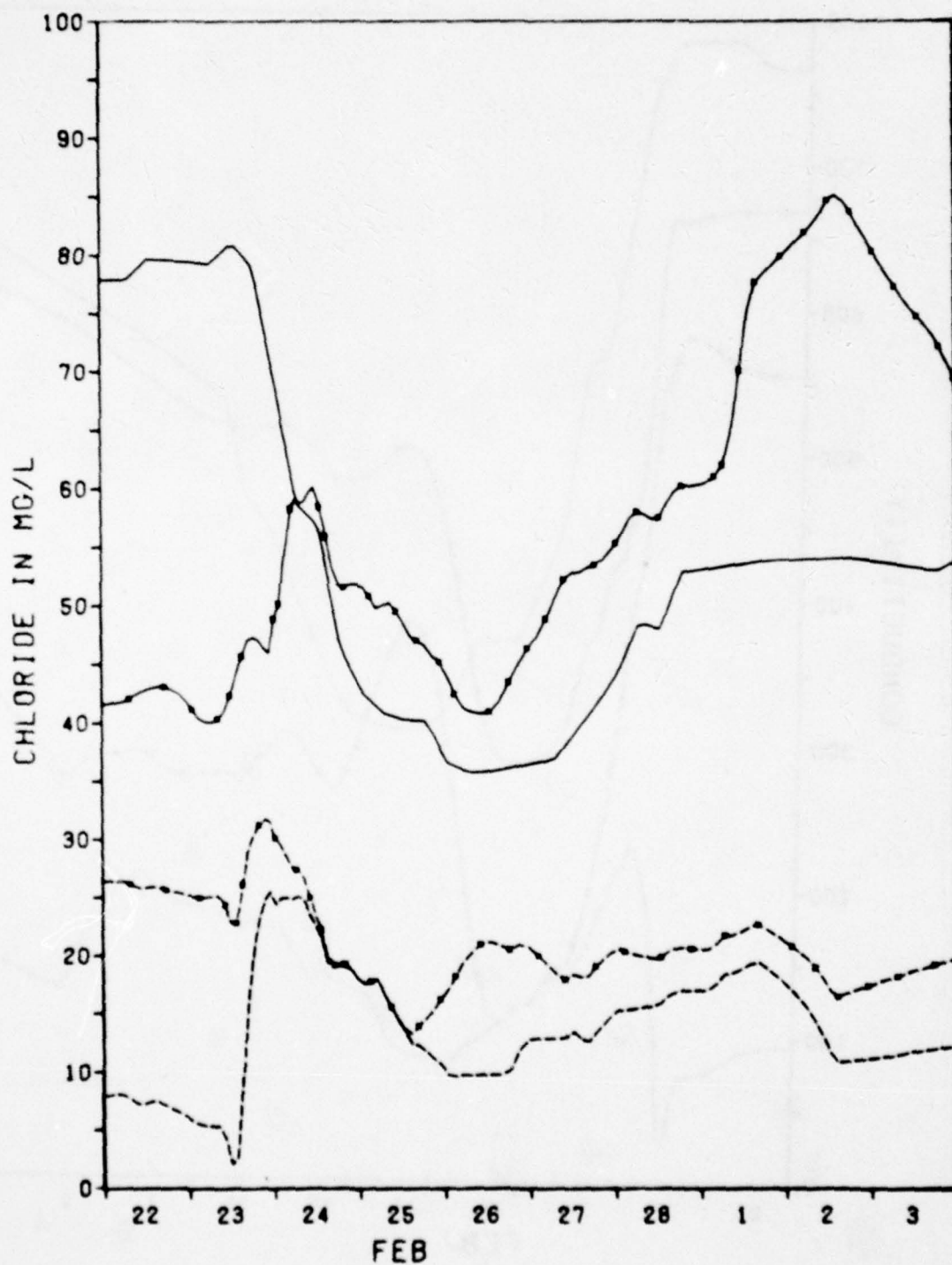
SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22

— MEASURED   ≡≡≡ BROKEN SWORD CREEK
•— CALCULATED   ≡≡≡ UNMEASURED
            ≡•≡ BUCYRUS

Figure 12f

32
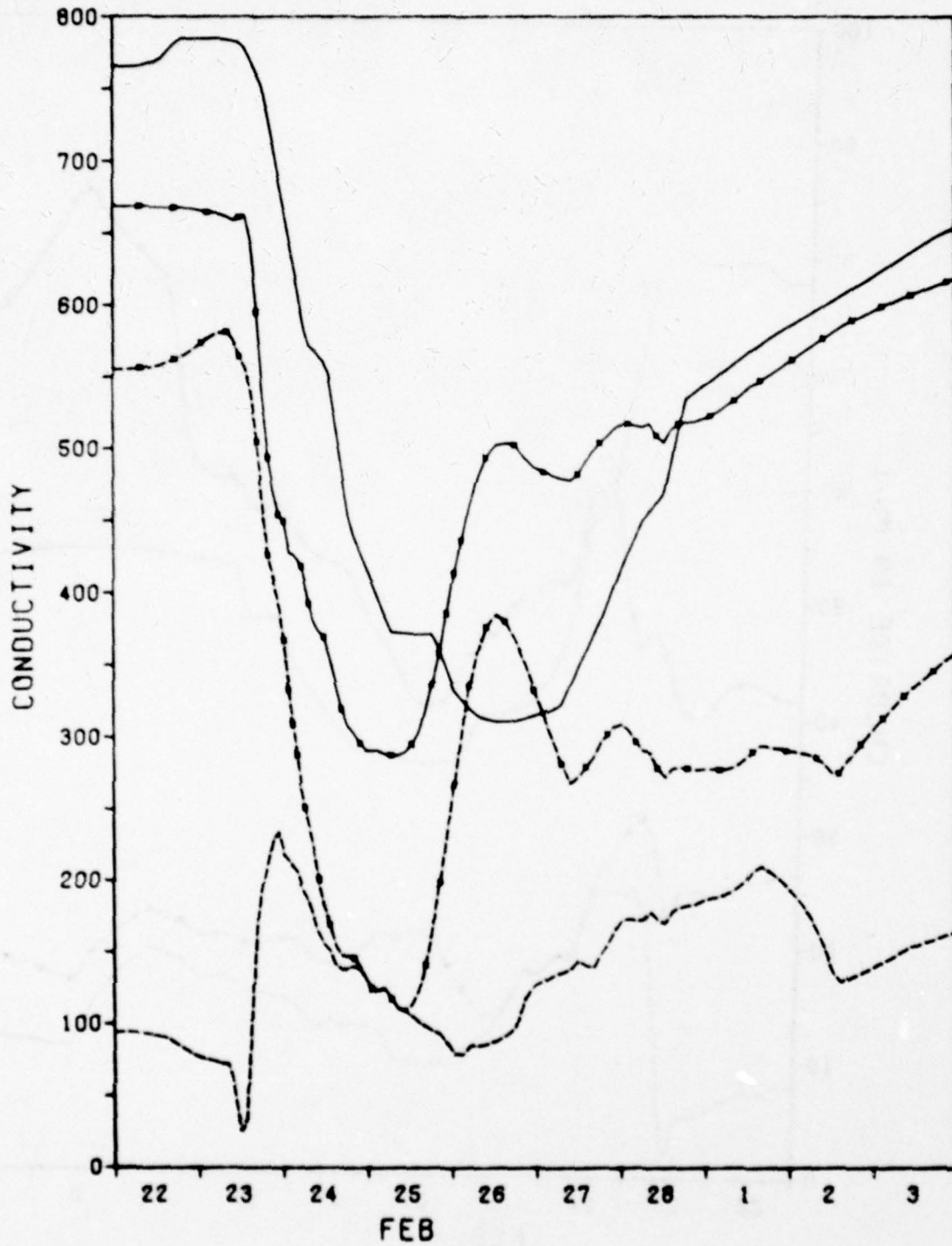
time they defined or redefined the discharge relationships at the stations used. The following results and plots are just to give an indication of what type of information can be derived from this procedure. Figure 6 illustrates a calculated and approximated ungaged inflow including the tributary of interest, Broken Sword Creek. This M is for the reach of Bucyrus to Upper Sandusky for the storm of 77/02/22. Figure 7 shows an excellent match on the downstream hydrograph for this storm.

For this reach, it was found that the ungaged inflow went negative at some periods of time when the tributary hydrograph for Broken Sword Creek was subtracted. Since this adjusted calculated M and the hydrograph for Broken Sword Creek are used in the water routing to define the chemistry, they are added together to define a new M. Figure 11 shows the resulting mismatch in the hydrograph as a result of this adjustment.

Figures 12a-12f, Figures 13a-13f, and Figures 14a-14f show the results for the Upper Sandusky, Mexico, and Fremont stations for the storm of 77/02/22. The material concentrations from unmeasured areas are assumed to be constant over the time period and are given in Table 1.

Sandusky River Near Upper Sandusky

Figure 12a shows the unmeasured inflow to be predominant only during the 22nd and 23rd. It can be expected to have relative influence on the chemistry only during this period.

Figure 12b shows resuspension of total phosphorus throughout the duration of the storm for an unmeasured lateral inflow concentration of 0.2 mg/l. Increasing the local inflow concentration to a high value would only have a major effect on the first two days. This may reduce the resuspension of total phosphorus during these days. The peak that shows up over the 1st and 2nd results from a spike at the Bucyrus station. This spike is represented by one high number in the data for this station. Since one measurement is involved, this may indicate an erroneous data point. However, since this same trend shows up for suspended solids and the station is just downstream of a sewage treatment plant, this point is probably real.

Figure 12c generally shows a loss of nitrate/nitrite nitrogen from the system for the unmeasured inflow concentration which was assumed in the computation.

Figure 12d shows a general resuspension of sediment from the bottom as would be expected with high flows. At the very beginning and end of the chemograph, deposition appears.

The comparisons between the measured and calculated chloride and conductivity are only fair. There are several reasons for the deviation between the predicted and measured concentrations; two are major reasons. First the actual data prior to the start of the storm was not used, the values at the start of the storm were pre-extended back so water traveling from the upstream station would reach the downstream station by the start of the storm. This problem exists for most of the storms discussed herein and it probably accounts for the mismatch at the start of the storms. Secondly, the

SANDUSKY RIVER NEAR MEXICO
STORM BEGINNING 77/02/22
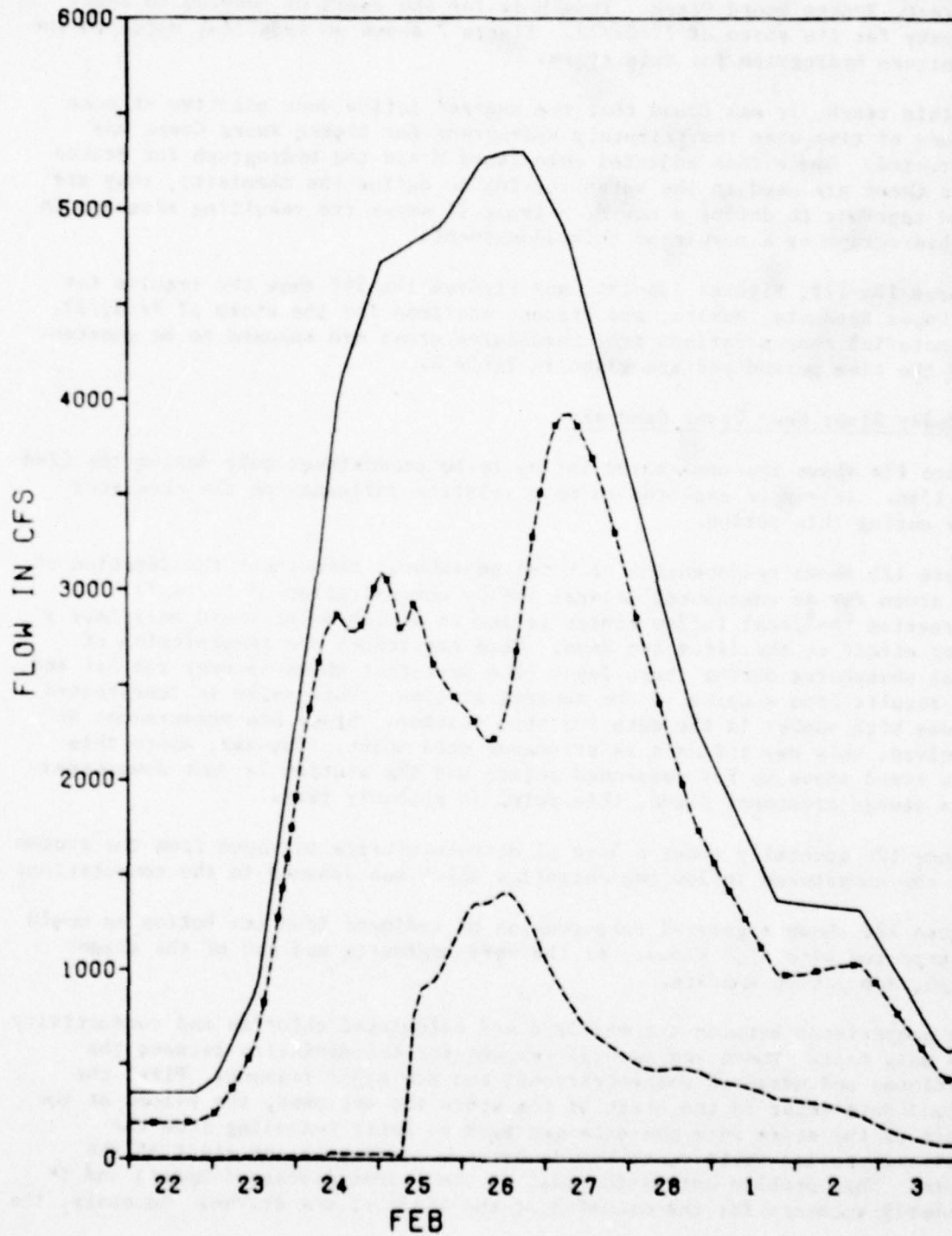—— MEASURED   ▪▪▪ UNMEASURED
▪▪▪ TYMOCHTEE CREEK   ▪▪▪ UPPER SANDUSKY

Figure 13a

SANDUSKY RIVER NEAR MEXICO
STORM BEGINNING 77/02/22
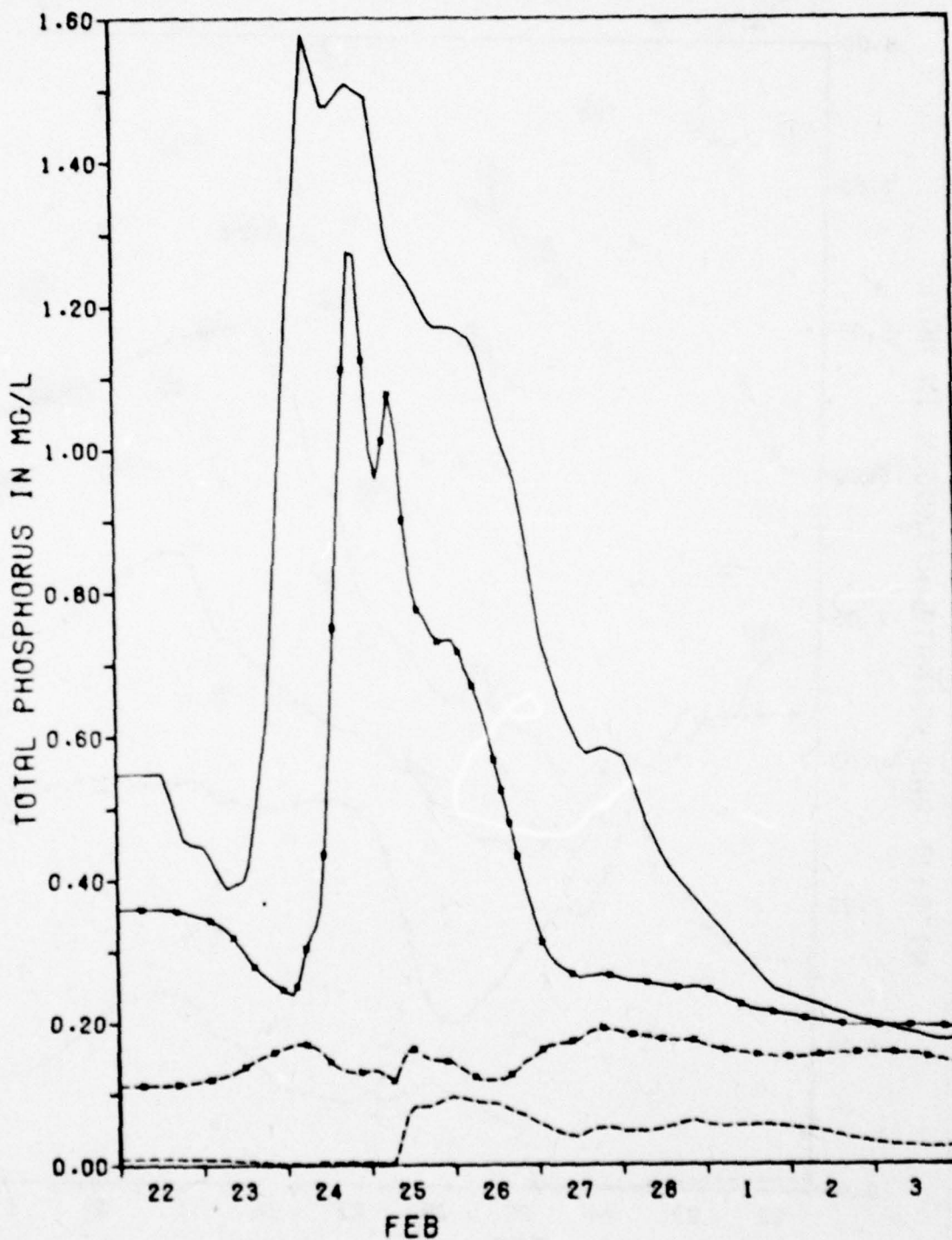
—— MEASURED	☲☲☲ UNMEASURED
•—• CALCULATED	☲•☲ UPPER SANDUSKY
☲☲☲ TYMOCHTEE CREEK	☲☲☲ RESUSPENSION
	☲☲☲ DEPOSITION
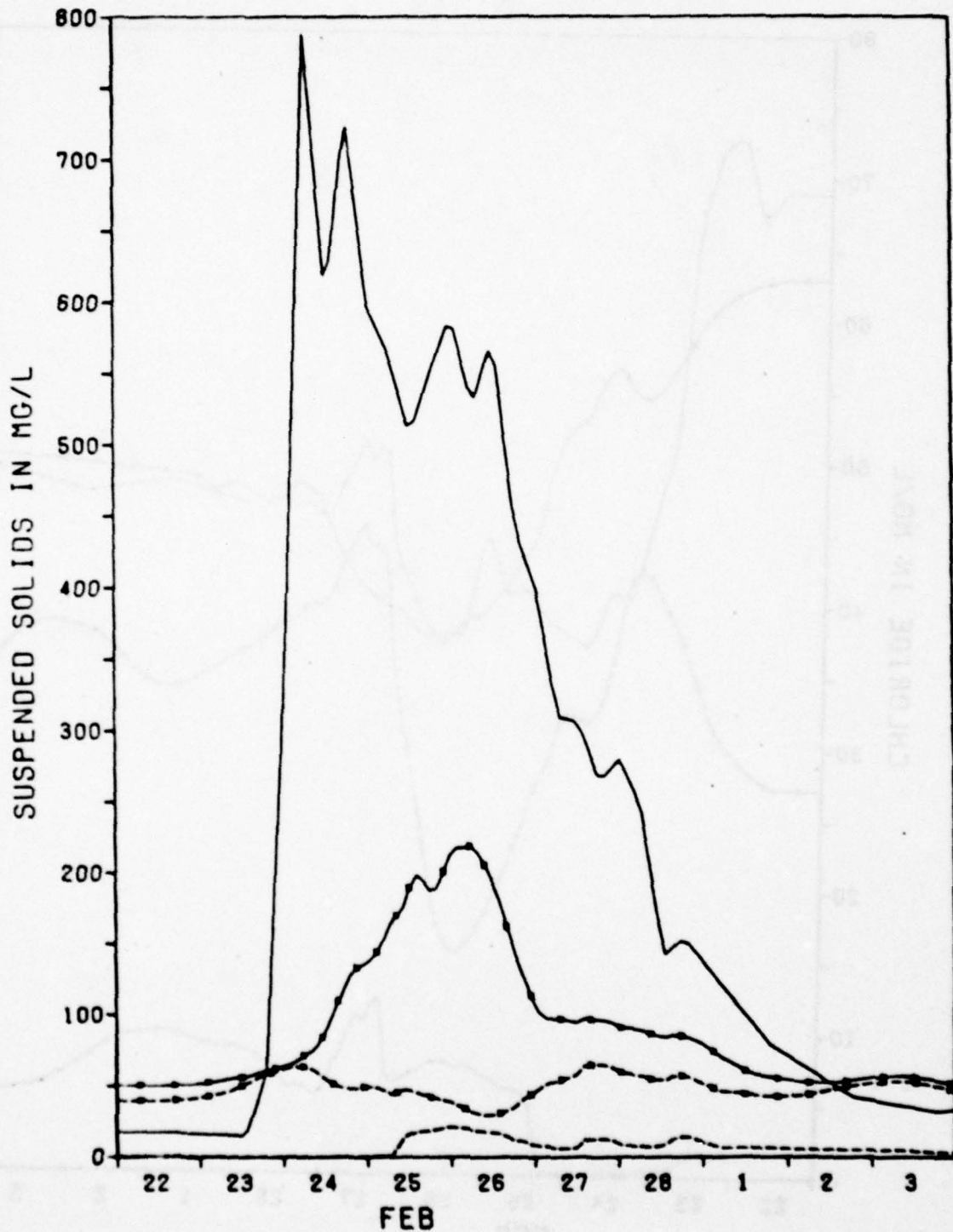
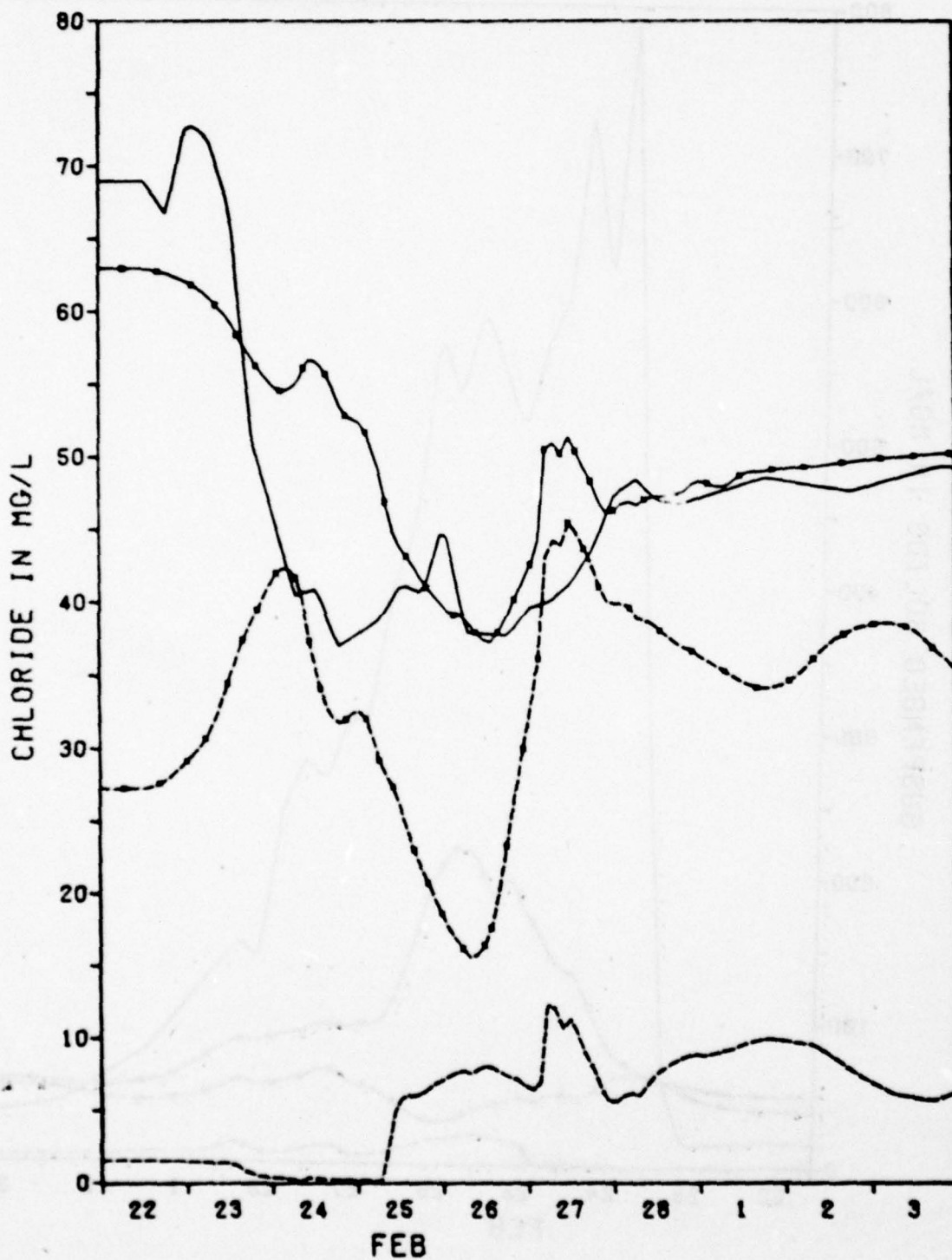Figure 13b

35

SANDUSKY RIVER NEAR MEXICO
STORM BEGINNING 77/02/22

——— MEASURED ————— TYMOCHTEE CREEK
—•— CALCULATED ——•• UNMEASURED
——•• UPPER SANDUSKY

Figure 13c

36

SANDUSKY RIVER NEAR MEXICO
STORM BEGINNING 77/02/22

Figure 13d

37

SANDUSKY RIVER NEAR MEXICO
STORM BEGINNING 77/02/22

——— MEASURED   ‾‾‾ TYMOCHTEE CREEK
●—● CALCULATED   ▪▪▪ UNMEASURED
▬▬▬ UPPER SANDUSKY

Figure 13e

SANDUSKY RIVER NEAR MEXICO
STORM BEGINNING 77/02/22
—— MEASURED   --- TYMOCHTEE CREEK
—•— CALCULATED   ••• UNMEASURED
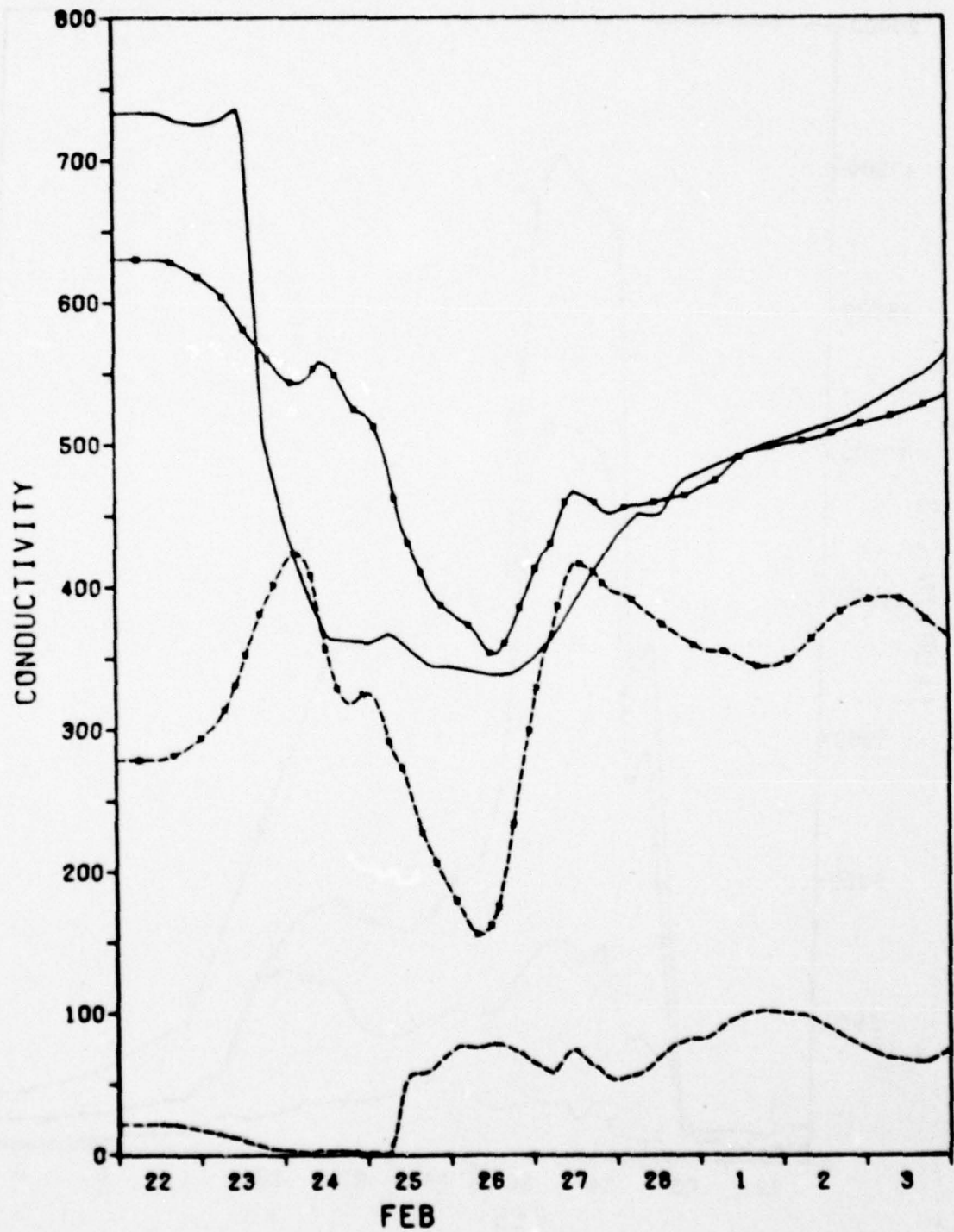•—• UPPER SANDUSKY

Figure 13f

39

SANDUSKY RIVER NEAR FREMONT
STORM BEGINNING 77/02/22
—— MEASURED   ——— WOLF CREEK
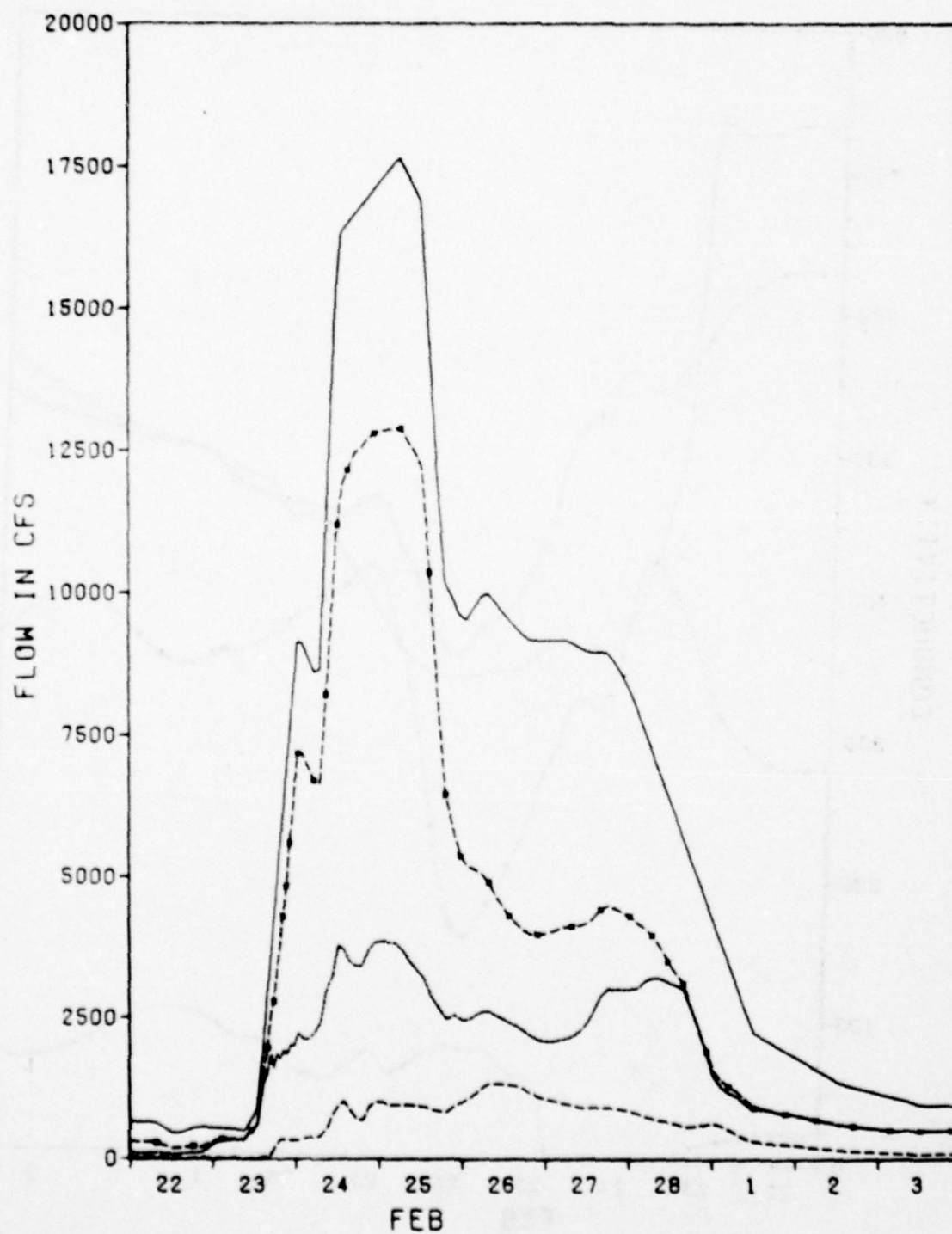——— HONEY CREEK   ••• UNMEASURED
——•— MEXICO

Figure 14a

40

SANDUSKY RIVER NEAR FREMONT
STORM BEGINNING 77/02/22

Figure 14b

41
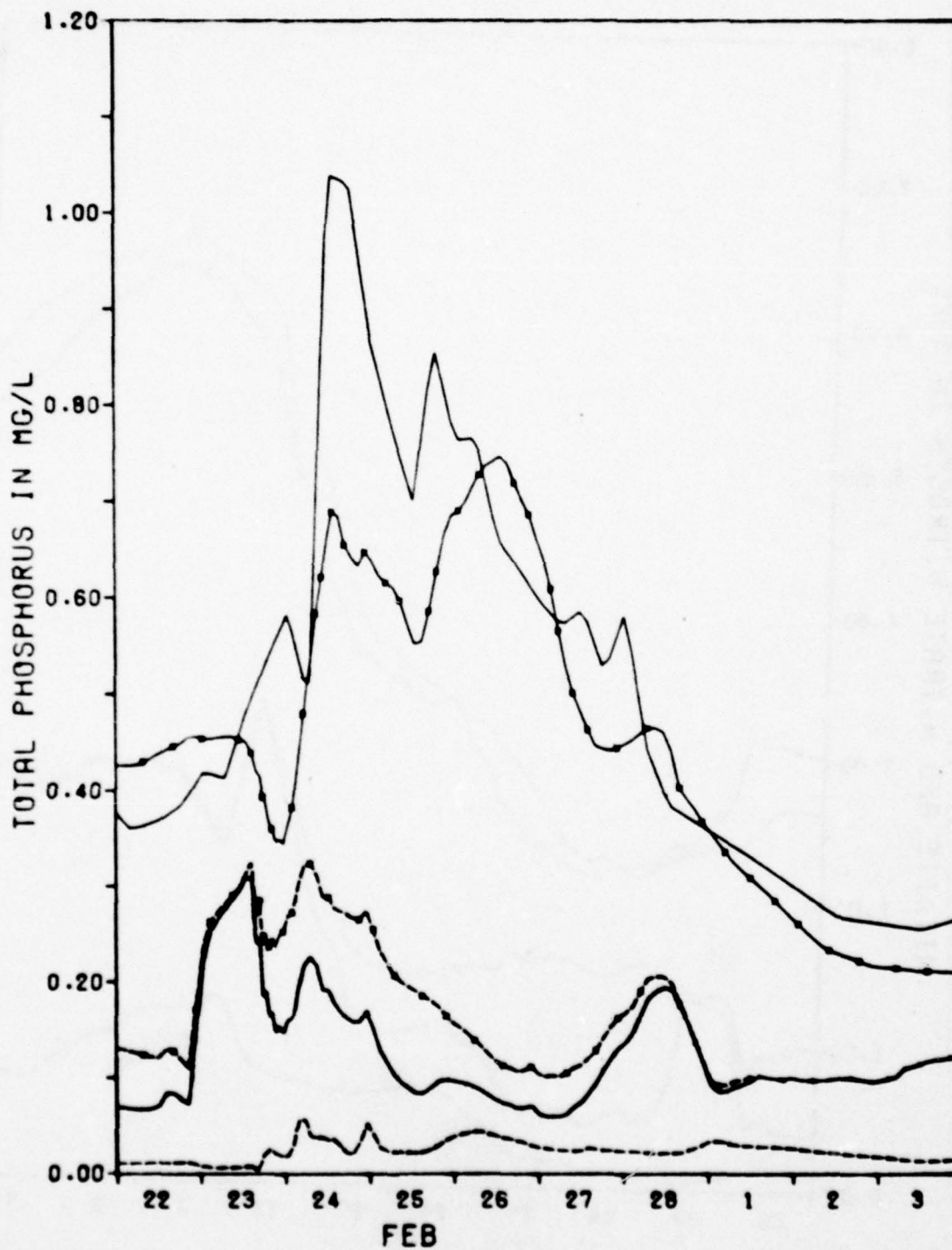
SANDUSKY RIVER NEAR FREMONT
STORM BEGINNING 77/02/22

—— MEASURED	⩶⩶ WOLF CREEK	
●● CALCULATED	⩶⩶ UNMEASURED	
⩶⩶ HONEY CREEK	●⩶● MEXICO	

Figure 14c

42

SANDUSKY RIVER NEAR FREMONT
STORM BEGINNING 77/02/22

Figure 14d

43

SANDUSKY RIVER NEAR FREMONT
STORM BEGINNING 77/02/22

Figure 14e

44

SANDUSKY RIVER NEAR FREMONT
STORM BEGINNING 77/02/22

Figure 14f

45

mismatch occurs because the unmeasured inflow concentrations were assumed constant when in actuality they are variable. Other minor contributions to the error could be variability in the area-discharge relationship or the neglection of dispersion of the flowing water.

Sandusky River Near Mexico

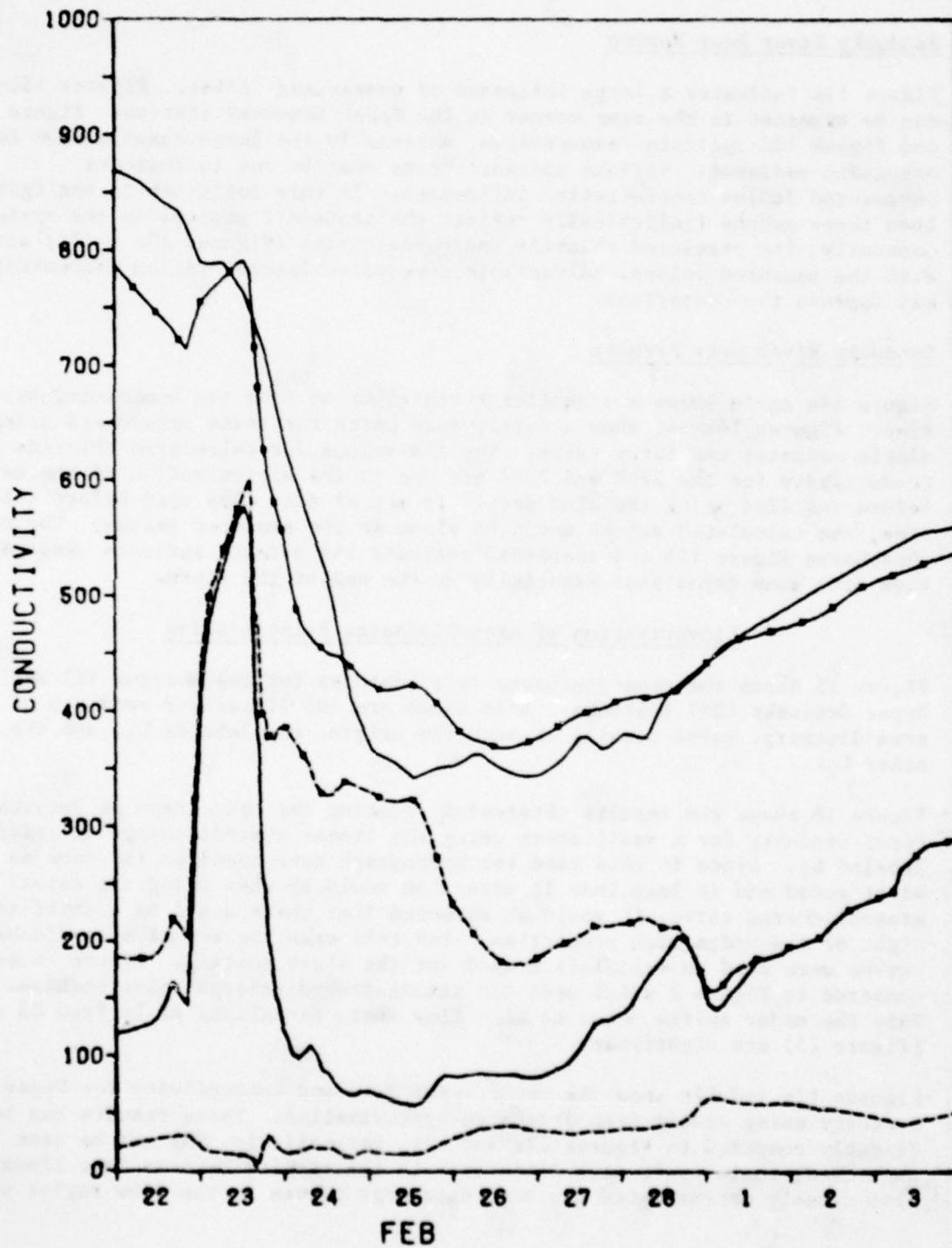Figure 13a indicates a large influence of unmeasured inflow. Figures 13b-13f can be examined in the same manner as the Upper Sandusky station. Figure 13b and Figure 13d indicate resuspension, especially the large resuspension for suspended sediment. Various concentrations must be run to indicate unmeasured inflow concentration influences. If this influence is negligible, then these graphs realistically reflect the transport process in the system. Generally, the predicted chloride and conductivity (Figures 13e & 13f) agree with the measured values. A variable unmeasured lateral inflow concentration may improve the comparison.

Sandusky River Near Fremont

Figure 14a again shows a significant contribution from the unmeasured basin area. Figures 14b-14f show a fairly good match for these parameters using a single nonpoint chemistry value. The low values for calculated chloride and conductivity for the 22nd and 23rd are due to the approximation of the data before the 22nd using the 22nd data. If actual data were used before this time, the calculated values would be close to the measured values. The total phosphorus Figure 14b and suspended sediment 14d primary indicate resuspension with some deposition especially at the end of the storm.

Linearization of Area-Discharge Relationships

Figure 15 shows the area-discharge relationships for the Bucyrus (B) and Upper Sandusky (US) stations. Also shown are two linearized versions of the area-discharge curve passing through the origin, one labeled L_1, and the other L_2.

Figure 16 shows the results obtained by routing the hydrograph at Bucyrus to Upper Sandusky for a small storm using the linear area-discharge relationship labeled L_1. Since in this case the hydrograph wave speed is the same as the water speed and is less than it otherwise would be when using the actual area-discharge curve, it would be expected that there would be a shift to the right of the hydrograph properties. For this case the actual area-discharge curves were used to calculate M used for the above routing. Figure 16 can be compared to Figure 7 which uses the actual area-discharge relationships. Note the major shifts occur at high flow where deviations of L_1 from US and B (Figure 15) are significant.

Figures 17a and 17b show the results for flow and conductivity for Upper Sandusky using linear area-discharge approximation. These results can be directly compared to Figures 12a and 12f, respectively. As can be seen in this case, there isn't much difference in the results because this linearization closely approximated the area-discharge curves in the flow region used.

FLOW IN CFS

16000

14000

12000

10000

8000

6000

4000

2000

0

US

β

L₂

L₁

0   450   900   1350   1800   2250   2700

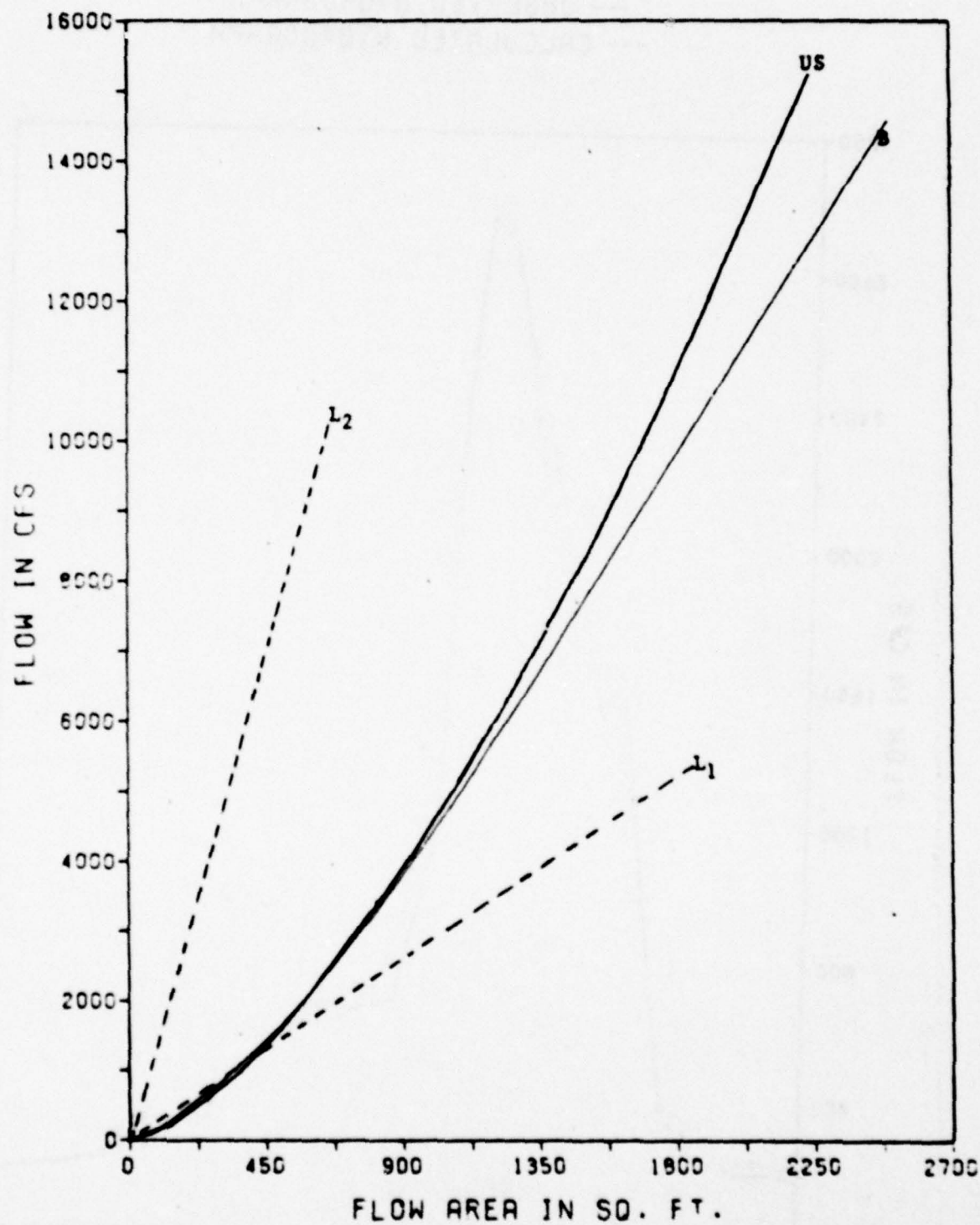FLOW AREA IN SQ. FT.

Figure 15

47

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22
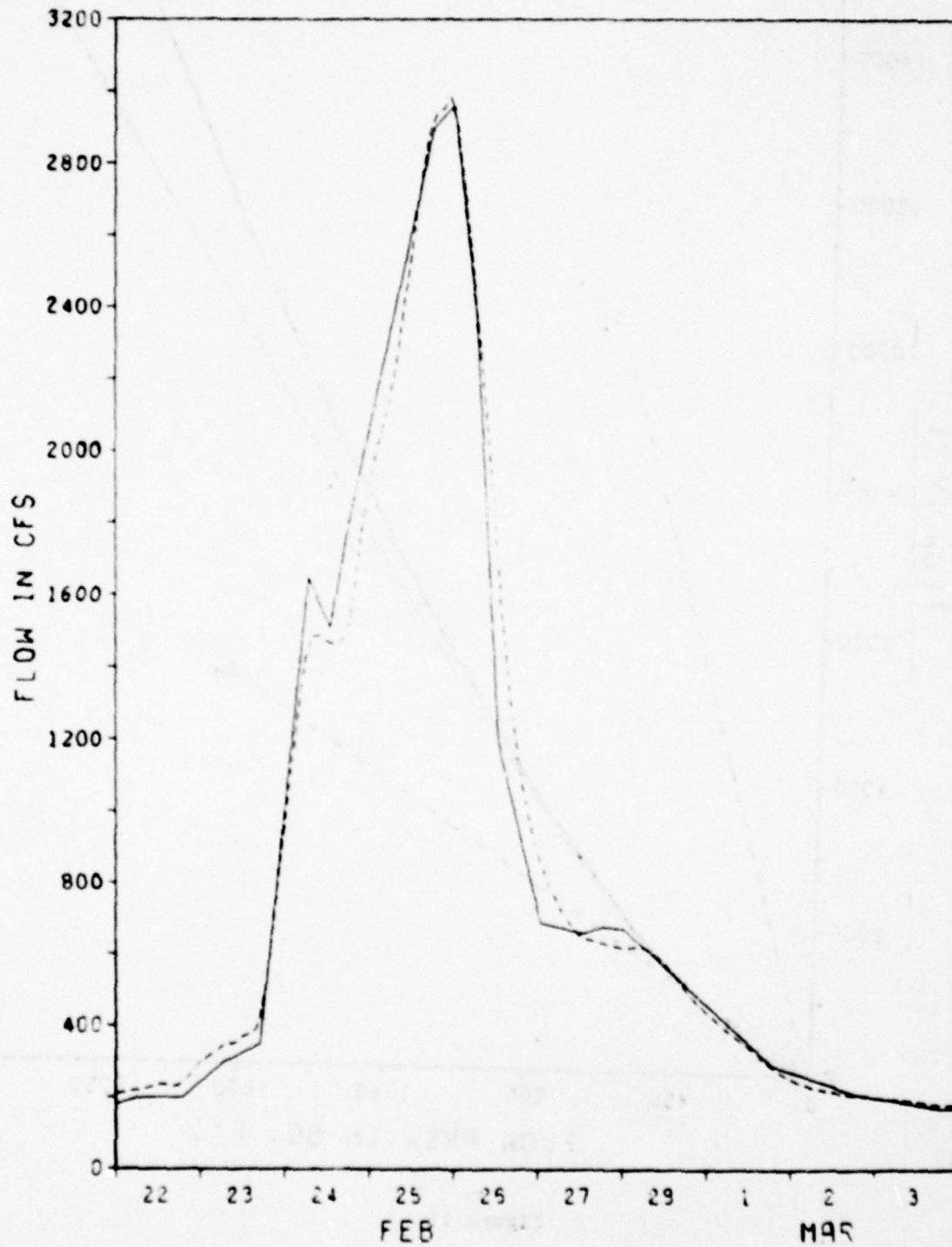—— OBSERVED HYDROGRAPH
--- CALCULATED HYDROGRAPH

Figure 16

48

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22

—— MEASURED   ═══ UNMEASURED
--- BROKEN SWORD CREEK   ═·═ BUCYRUS

Figure 17a

49

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22

—— MEASURED   ⎯⎯ BROKEN SWORD CREEK
•—• CALCULATED   ⎯•⎯ UNMEASURED
••⎯•• BUCYRUS

Figure 17b

50

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22
—— MEASURED ::: UNMEASURED
--- BROKEN SWORD CREEK --- BUCYRUS

Figure 18a

51

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22
—— MEASURED   ⁃⁃⁃ UNMEASURED
⁃⁃⁃ BROKEN SWORD CREEK   ⁃⁃⁃ BUCYRUS

Figure 18b

52

SANDUSKY RIVER NEAR UPPER SANDUSKY
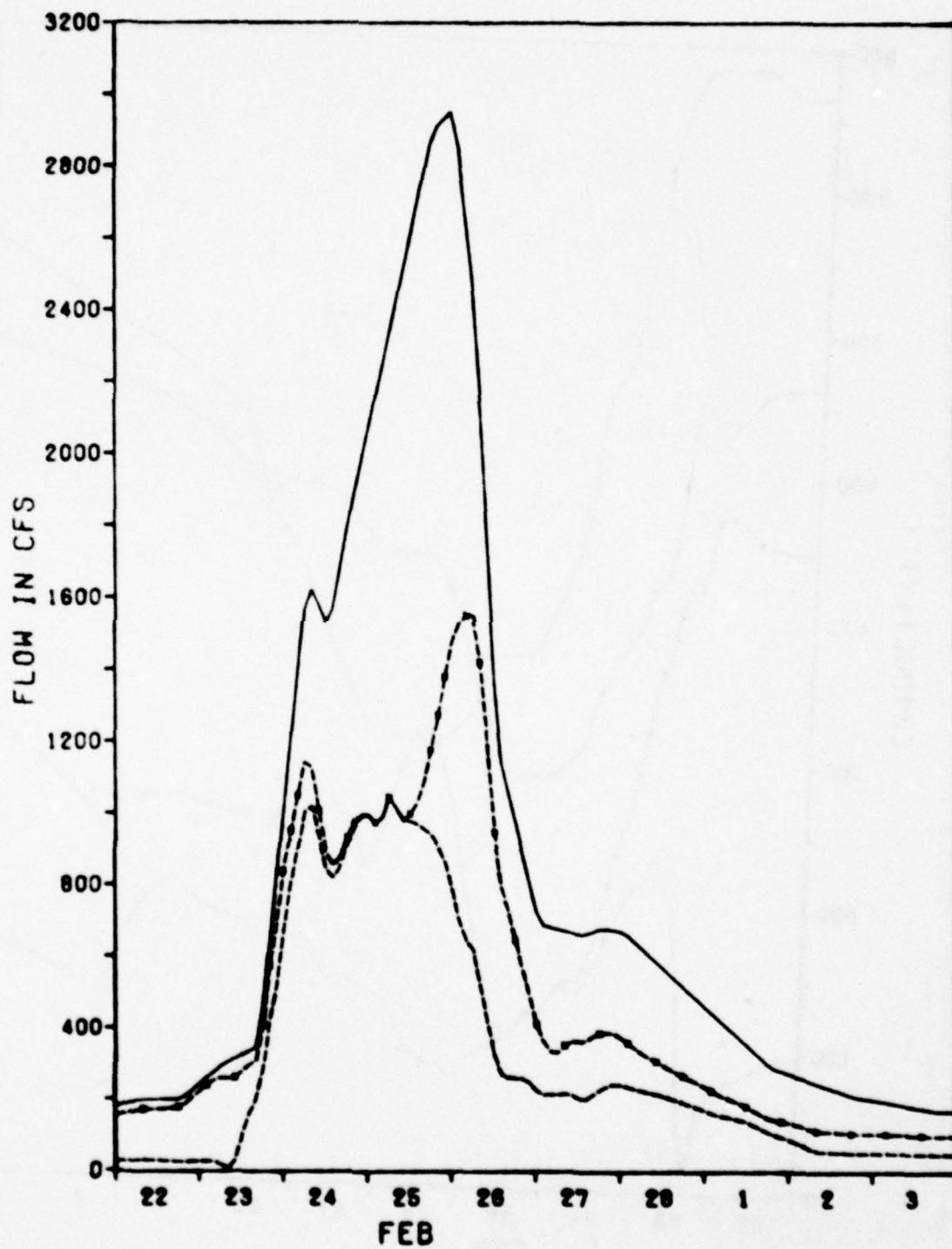STORM BEGINNING 77/02/22

Figure 18c

53

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22
—— MEASURED   ⁻⁻⁻ BROKEN SWORD CREEK
•— CALCULATED   ⁼⁼⁼ UNMEASURED
⁼⁼⁼ BUCYRUS

Figure 19a

54

SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22

—— MEASURED   ⚏⚏⚏ BROKEN SWORD CREEK
•— CALCULATED   ⚏⚏⚏ UNMEASURED
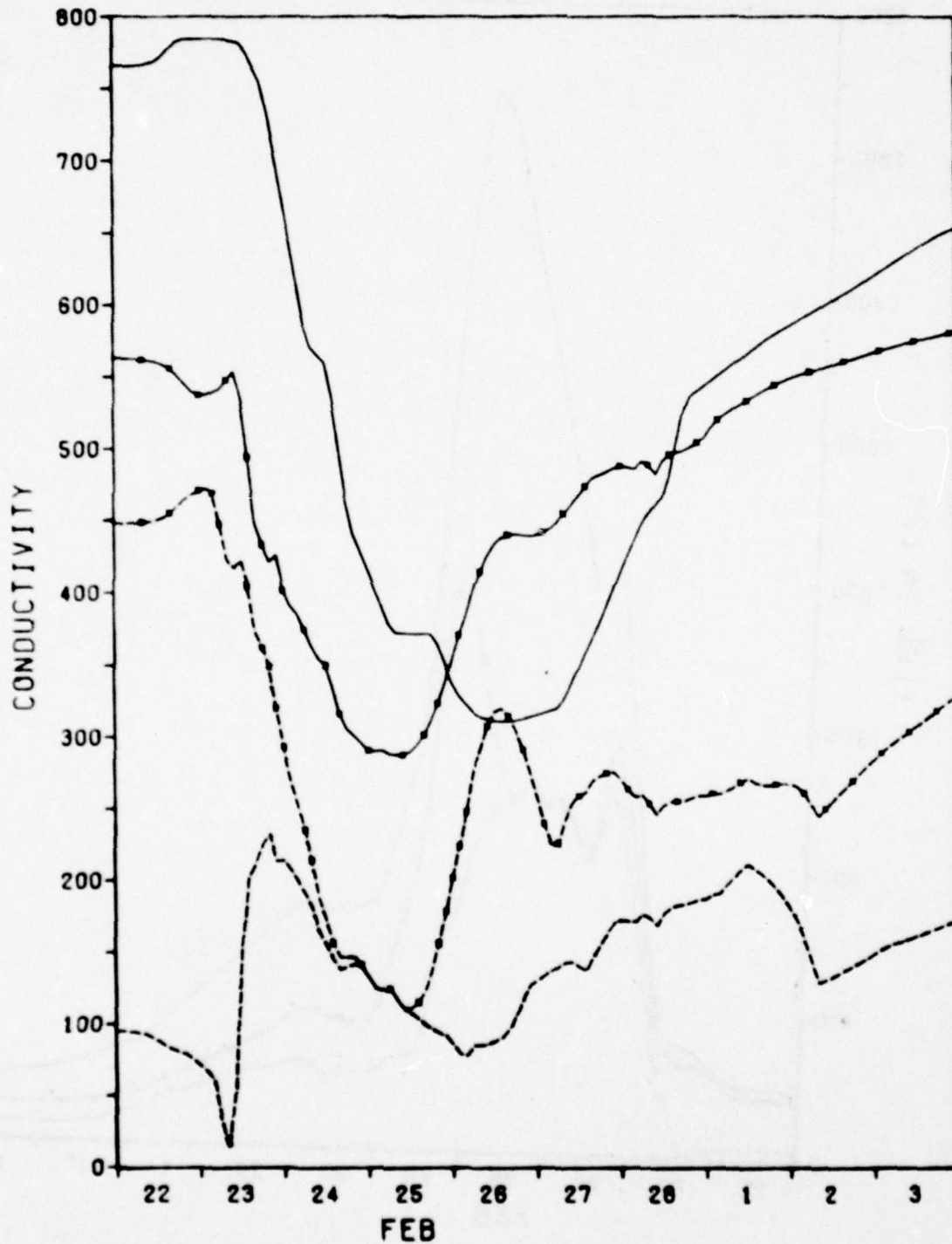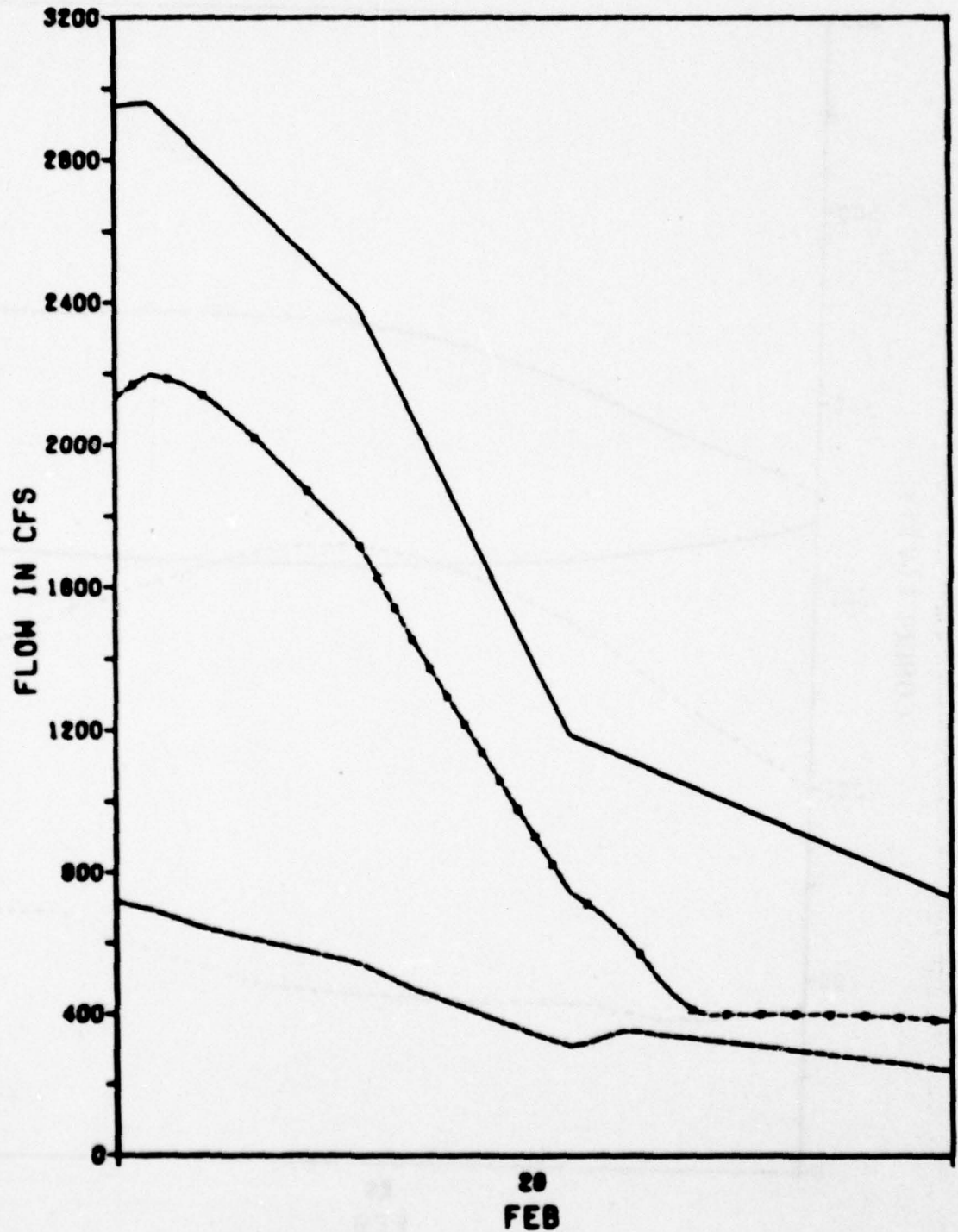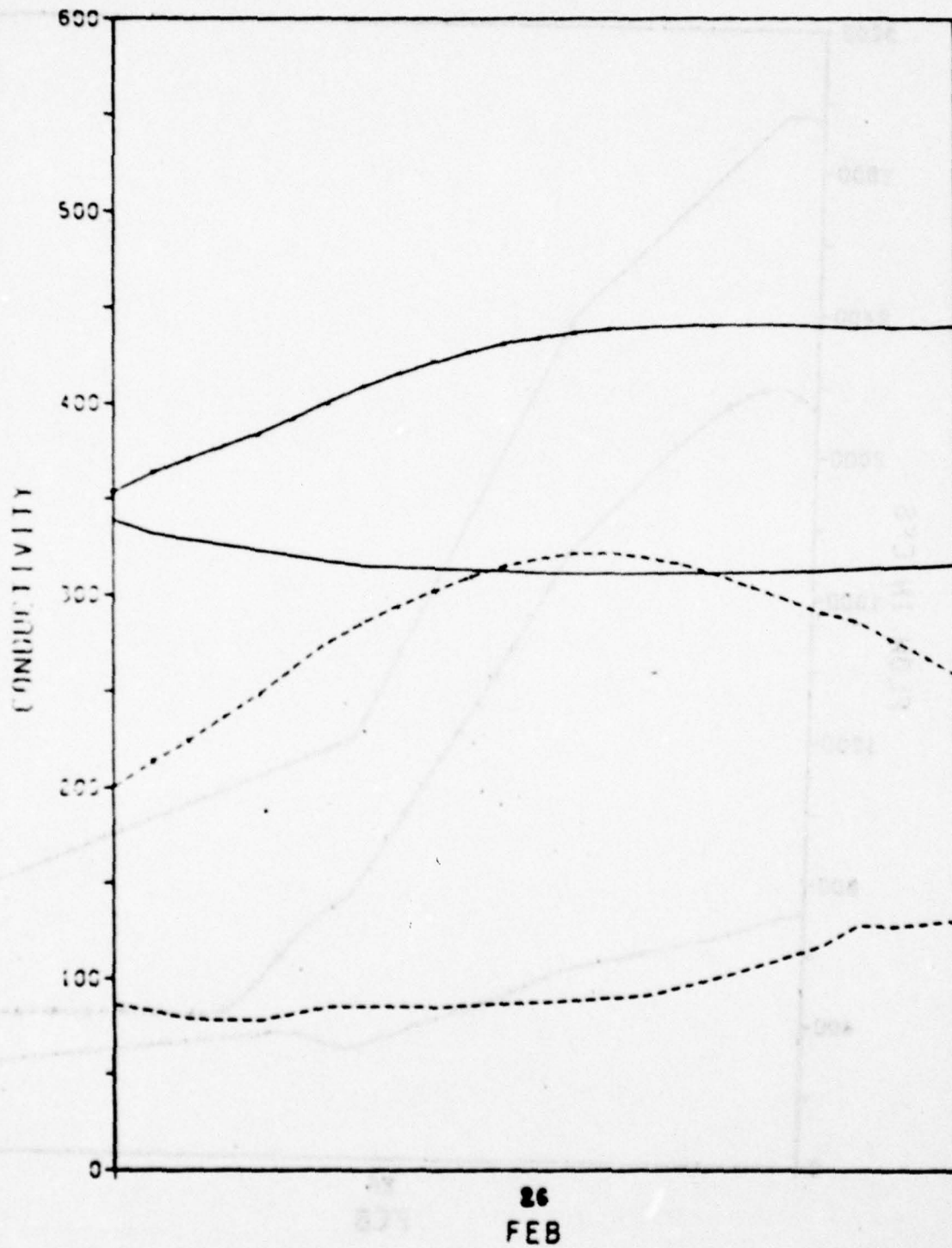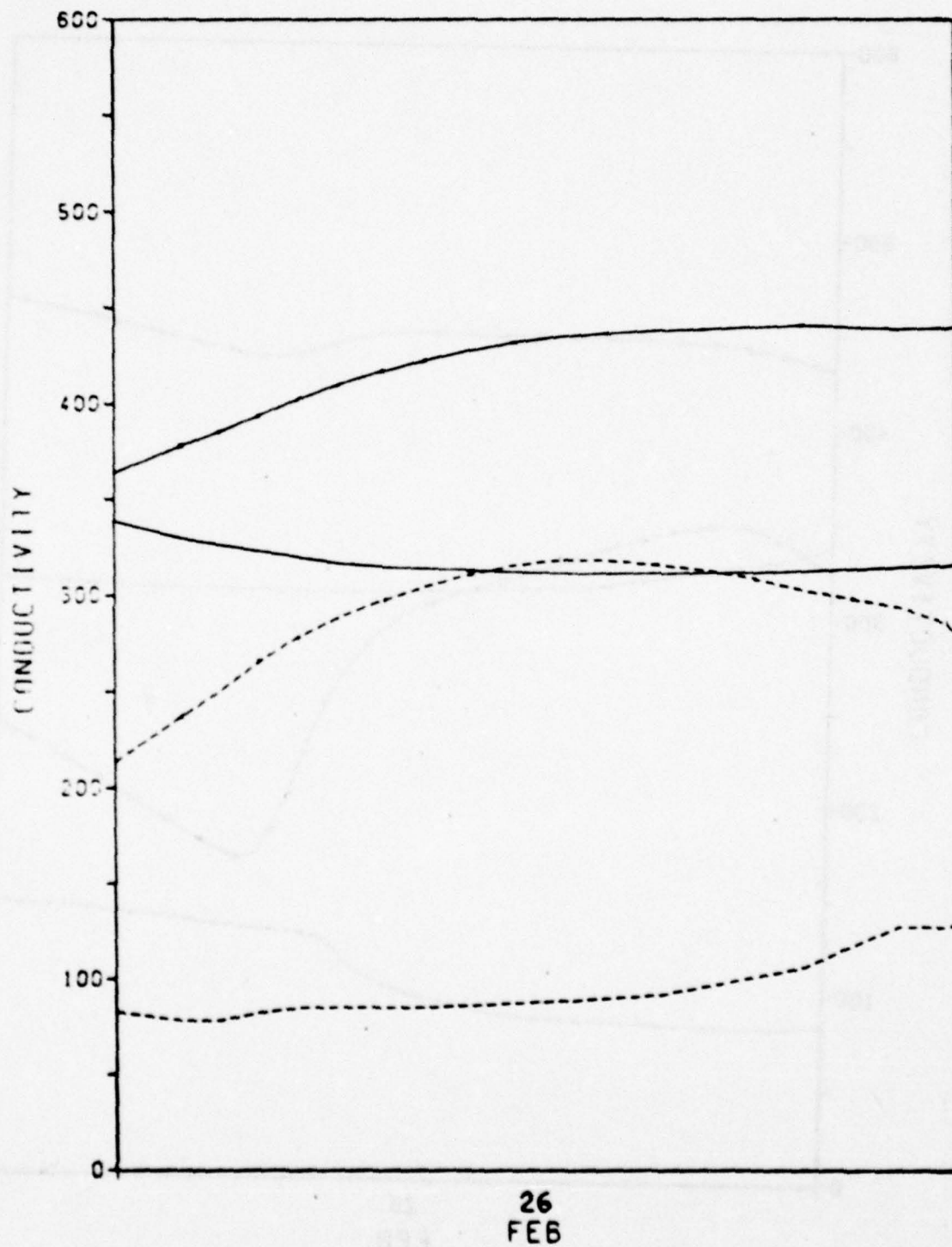⚏⚏⚏ BUCYRUS

Figure 19b

55

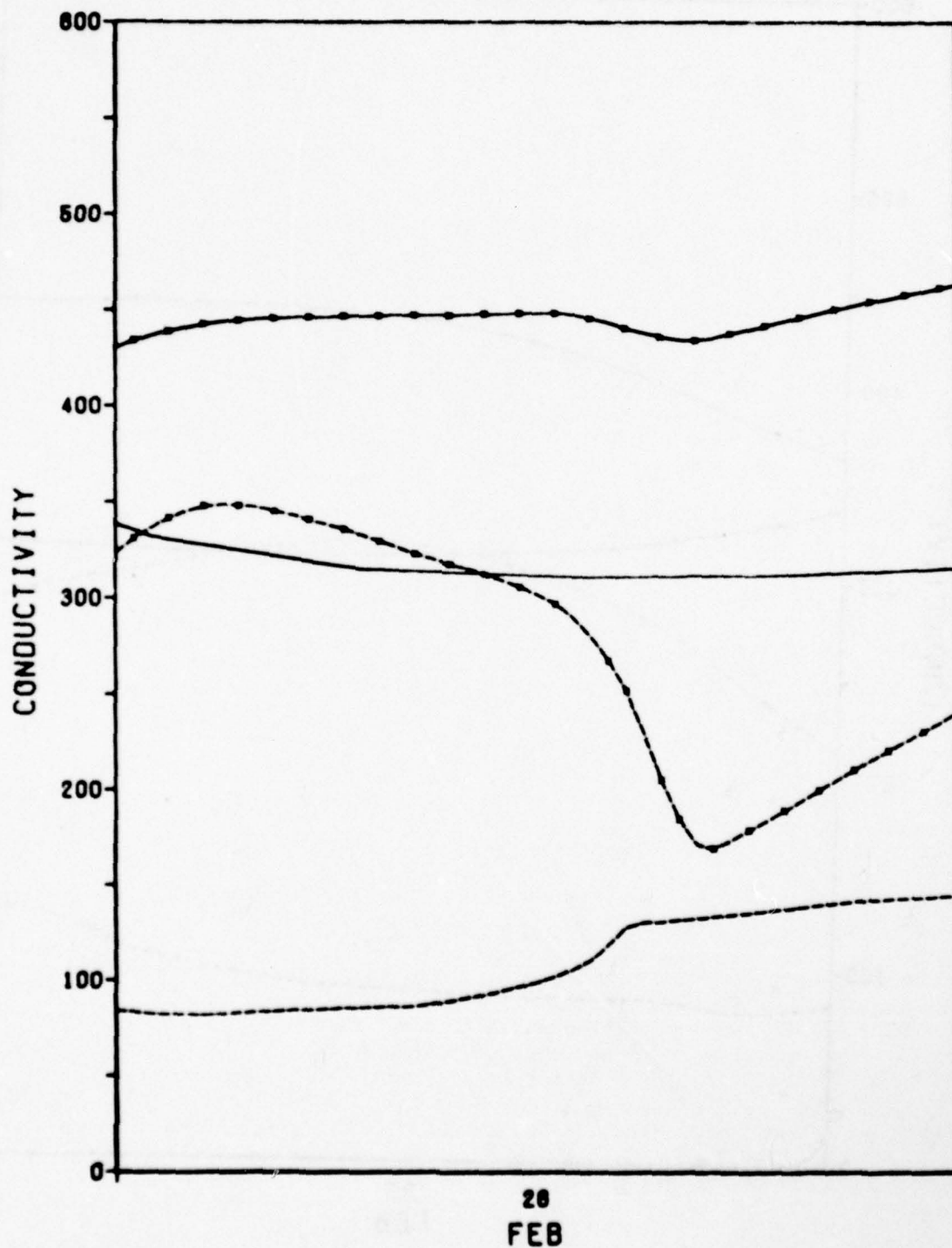SANDUSKY RIVER NEAR UPPER SANDUSKY
STORM BEGINNING 77/02/22

Figure 19c

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Figures 18a-18c show the results for one day, February 26, for discharge. Figure 18a is the flow pattern for the actual area-discharge curves, B and US, while Figure 18b is for L_1, and Figure 18c for L_2. As can be seen, there are slight differences between Figures 18a and 18b, while for Figure 18c there is a shift of almost half a day in the curve properties to the left. There is also a change in the magnitude of the results. This shift and changes in magnitude can be expected because the water is now forced to travel faster than it traveled before by using L_2 instead of B and US in Figure 15; therefore, the water would arrive sooner downstream and the tributary and nonpoint flows would influence different parts of the water at Upper Sandusky as it traveled downstream than would have been influenced before.

Figures 19a-19c show the same type of results for conductivity for the same day using a nonpoint concentration of 500 micro mhos at 25°C. As can be seen, the changing of the area-discharge curves causes a shift in the predicted profiles primarily because the properties of the water from different sources is shifted in time.

Time Varying Inputs

Figure 20 shows a time varying nonpoint inflow concentration for conductivity while Figure 21 shows the results. This figure is compared with Figure 13f. As can be seen if sufficient information is known to define a variable lateral inflow concentration, the chemistry may be approximated more accurately. The assumed profile in Figure 20 is probably realistic since it corresponds to the general shape of the conductivity concentration in the river, i.e. Figure 21.

Figures 22 and 23 show similar results for total phosphorus. Note the relatively insignificant changes when compared to Figure 13b. Even by increasing the inflow concentration to high values, there is no significant changes during the storm even though the nonpoint inflow is relatively large. Large changes are seen only during low flow. This illustrates that inflow concentrations cannot account for the variations and therefore, resuspension occurs throughout this storm. At the peak period of flow, the flow from Upper Sandusky predominates and, because of this, the chemistry at Upper Sandusky predominates as seen in the calculated peak during the 25th as seen in Figure 13b.

Instream Processing of Phosphorus

Figure 24 illustrates how the calculational procedure can be used to understand the instream processing of point source phosphorus. This example is for the Upper Sandusky station which is downstream of a sewage treatment outfall. During low flow, both total and ortho phosphorus are lost from the water column. During high flow, total phosphorus is resuspended while no ortho phosphorus is removed from the sediments. This figure shows how immediately available ortho phosphorus is lost from the water column and is subsequently resuspended and delivered to the lake during a storm as potentially available phosphorus.

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UPPER SANDUSKY TO MEXICO

77/02/22

UNMEASURED INFLOW CONCENTRATION
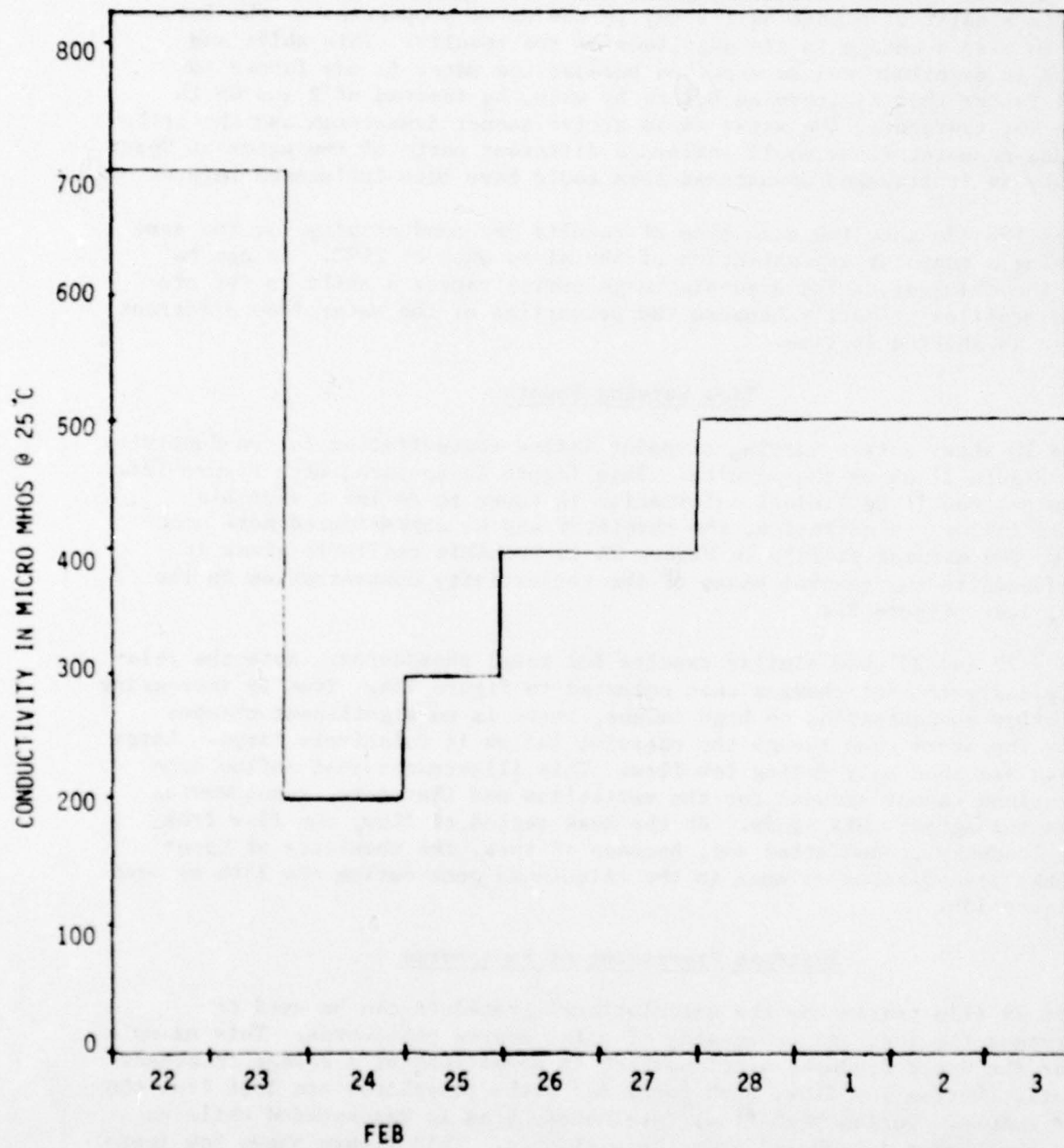
Figure 20

SANDUSKY RIVER NEAR MEXICO
STORM BEGINNING 77/02/22

Figure 21

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UPPER SANDUSKY TO MEXICO

77/02/22

UNMEASURED INFLOW CONCENTRATION
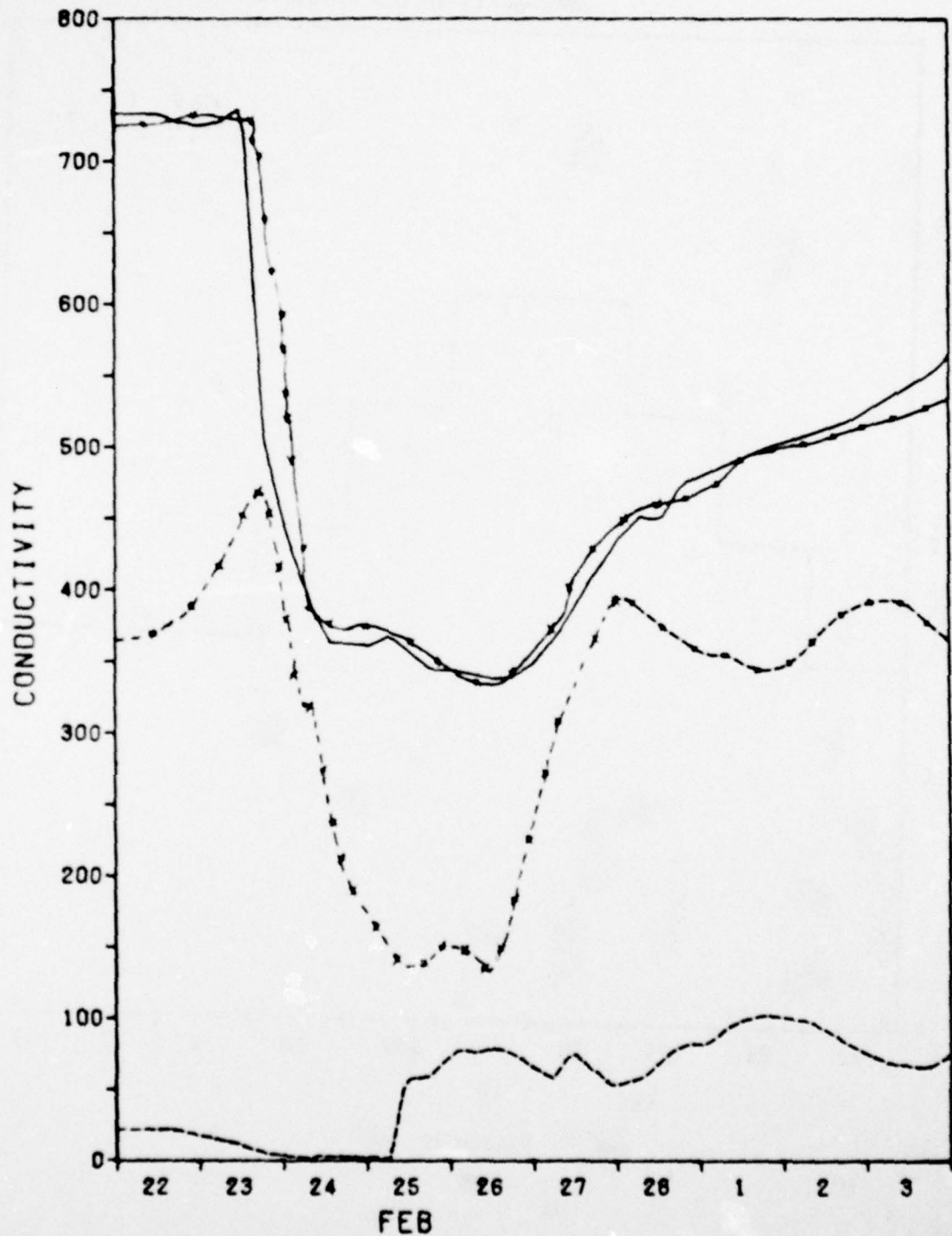

Figure 22

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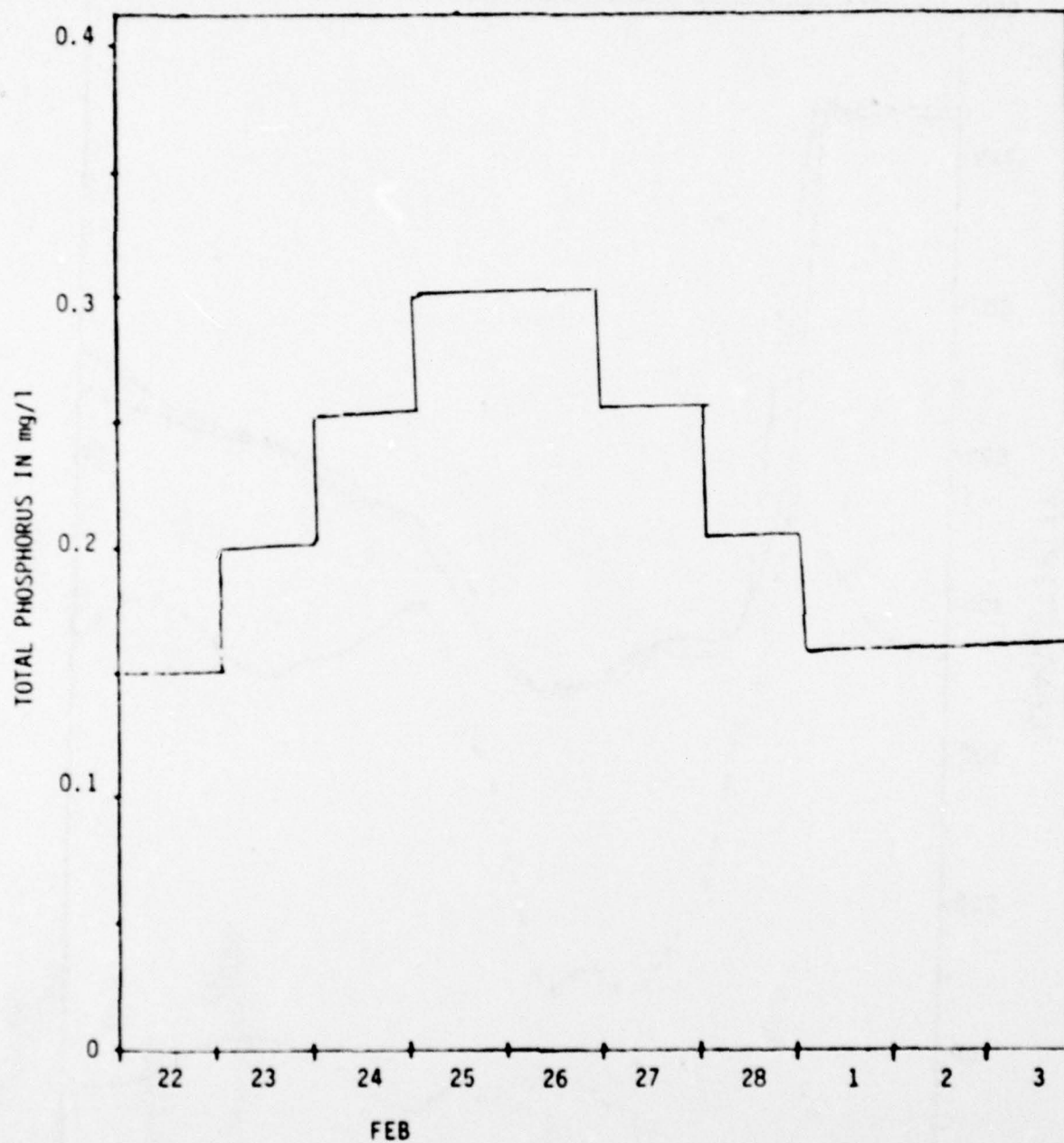
SANDUSKY RIVER NEAR MEXICO
STORM BEGINNING 77/02/22

— MEASURED
•—• CALCULATED
‑‑‑ TYMOCHTEE CREEK
⊐‑⊐ DEPOSITION
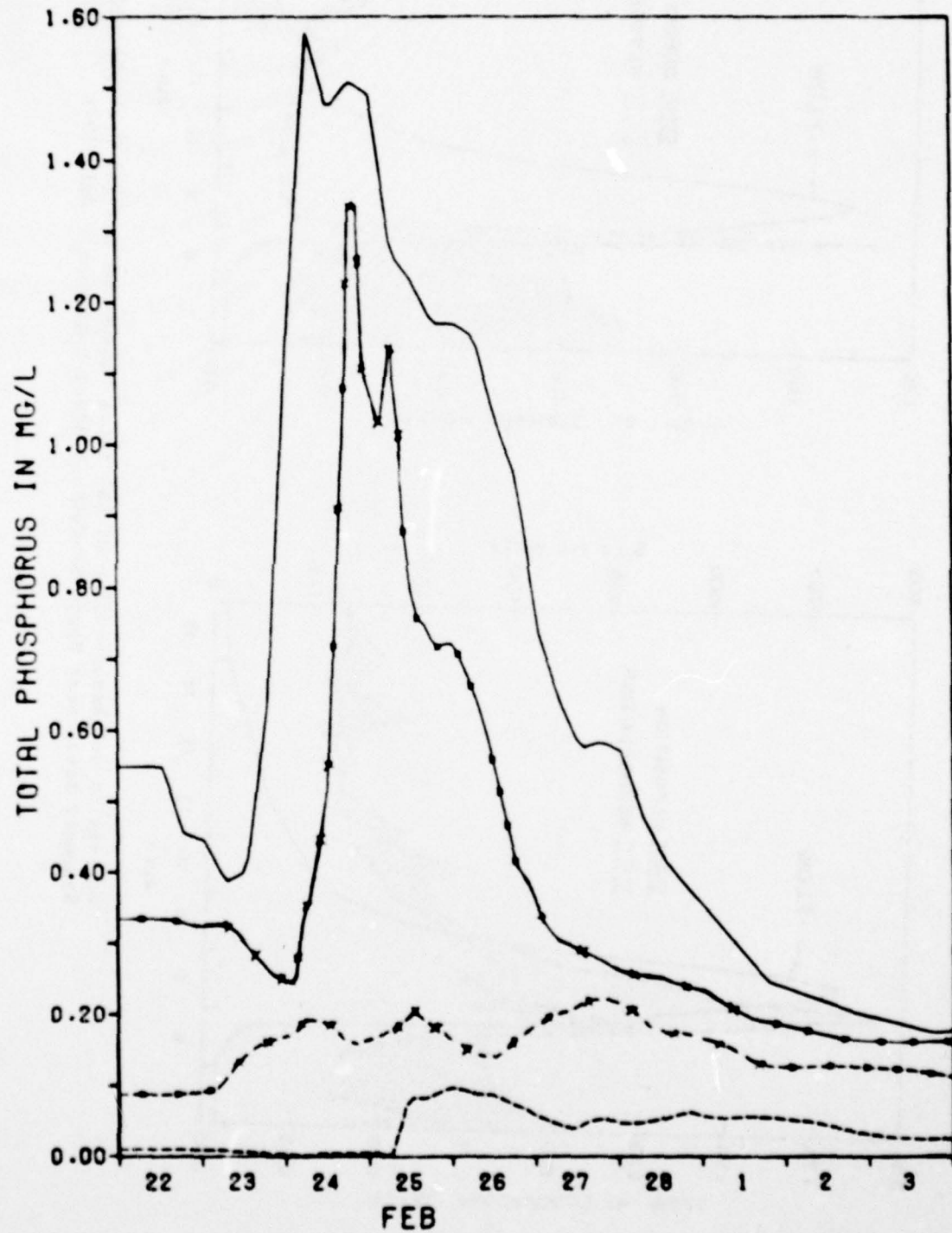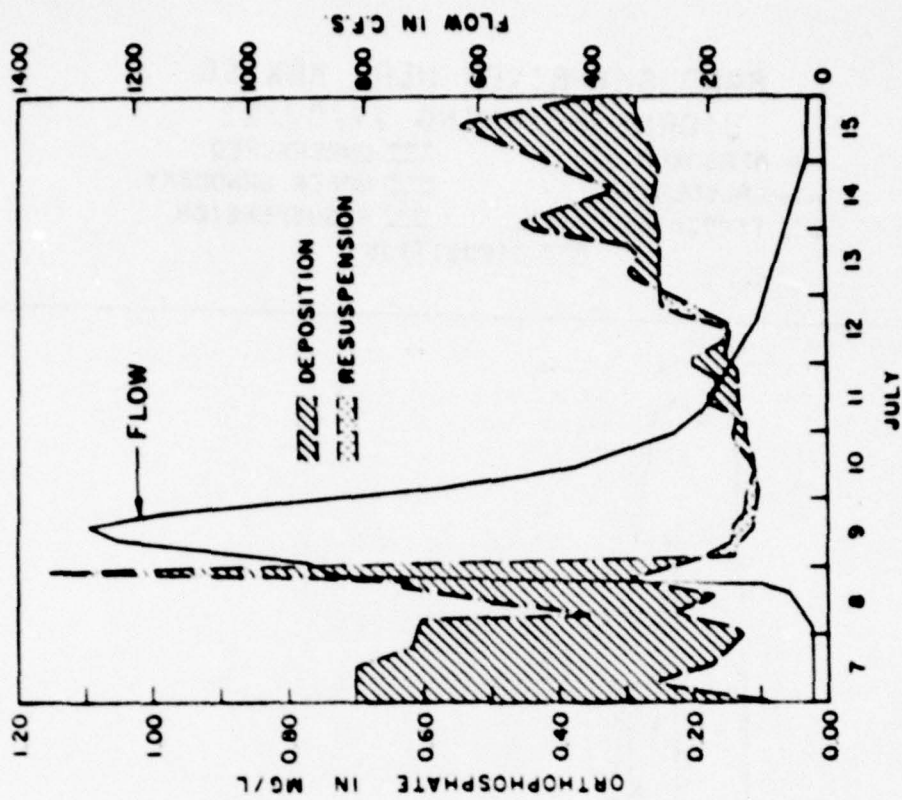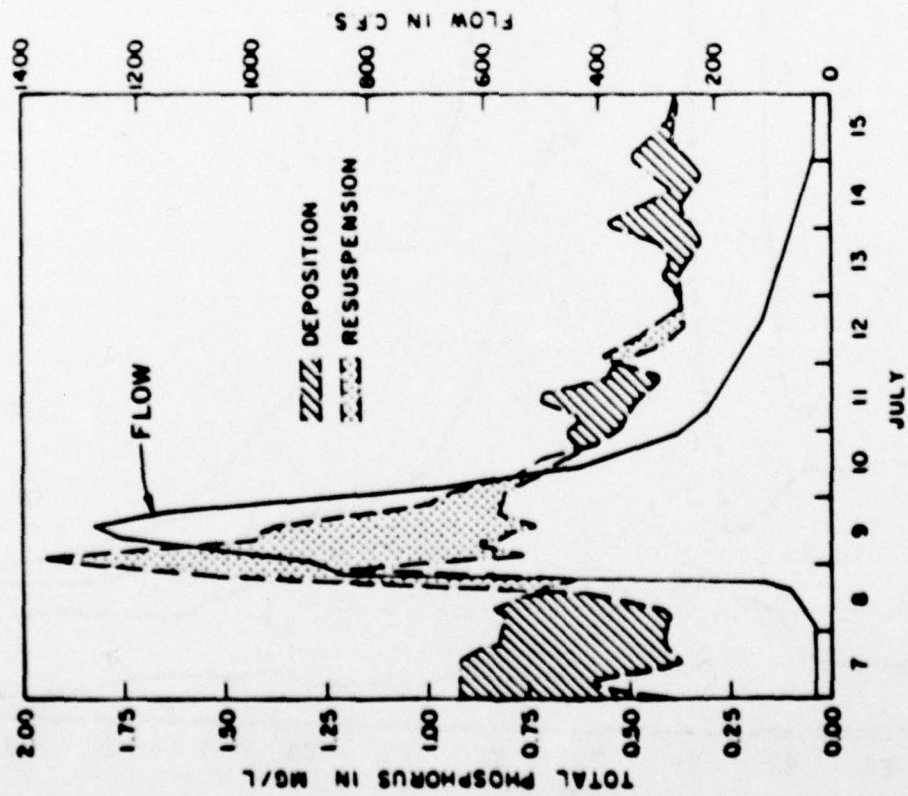‑‑‑ UNMEASURED
⊐‑⊐ UPPER SANDUSKY
⊐‑⊐ RESUSPENSION

Figure 23

Deposition and Resuspension of (a) Total Phosphorus and (b) Orthophosphate in the Sandusky River near Upper Sandusky - Storm beginning 7 July 1976

Figure 24

A study of different storms on the Sandusky River basin has indicated net deposition to occur during low steady flows and small storms for some reaches while net resuspension occurs for large storms. The reach from Bucyrus to Upper Sandusky generally shows net resuspension for all storms. Presumedly, the material that is resuspended is deposited during low flows between storms with much material coming from the sewage treatment plant below Bucyrus. For the reach from Upper Sandusky to Mexico net deposition occurs during small storms. Presumedly, a small dam above Mexico aids in the deposition. The reach from Mexico to Fremont shows net resuspension for nearly all storms. Low steady flow causes net deposition in all reaches. An important fact resulting from this study is that about half of the total phosphorus entering Lake Erie resulted from resuspension of material in the main stream of the river. Most of this material was initially derived from the land surface.

Total Water Balance Check on Accuracy

Table 2 shows a comparison of the total volume of water for this storm calculated by different methods which is a check of the accuracy of the calculational procedure for a particular storm. Two sources of numbers are depicted as major column headings. These are further divided into results depicting data which exclude and include the listed tributaries from the unmeasured lateral inflow, respectively. The total line indicates the total of the sources for the particular reach. Following this is the measured amount at the station. These two lines should be in fairly close agreement for good accuracy. The next line indicates the starting source for the next reach. There are two sources of error attributed to these numbers. The first, which is small, is due to numerical integration of the areas under the curves and rounding to significant figures. The second source, which could be major, is due to downstream hydrograph mismatch as an example shown in Figure 11. This occurs when the tributaries of interest are included separately in the calculations and their water volumes are subtracted from the unmeasured lateral inflow for the reach with the result being adjusted as not to go negative. The mismatch volume is used in the calculational procedure with the resulting percentages being applied to the actual water volume to get the numbers in the column titled "Calculational Procedure." This generally causes a minor discontinuity between stations (the total for the reach and measured do not agree). The amount of error is checked by computing fractional volumes where the tributaries are included under the unmeasured lateral inflow for the reach. For example, for the reach from Bucyrus to Upper Sandusky the results where the tributaries are not broken out agree closely. When Broken Sword Creek is separated from the unmeasured inflow the total for the reach is 760 as compared to the measured amount of 733 as shown in column 1. Column 3 shows the calculational procedure volumes which are based on the measured flow of 733. Because of this there is some error introduced in the volumes as shown when these are compared to the numbers in column 4.

Total Phosphorus Balance

Table 3 shows a comprehensible total phosphorus mass balance for the Sandusky River for the storms of 77/02/22 which lasted for 10 days as derived by finding the area under the total phosphorus fraction graphs such as the one in Figure 12b derived by fraction calculation. The budget must be viewed in

Table 2 - Comparison of the Total Volume of Water
Storm of 77/02/22
(All volumes are in millions of cubic feet)

Sources - From Bucyrus to Fremont	From Input Data		Calculational Procedure	
Bucyrus	350*	350*	321	352
Broken Sword Creek	267	–	268	–
Unmeasured	143	383	144	382
Total (Bucyrus to Upper Sandusky)	760	733	733	733
Upper Sandusky*	733	733	733	733
Upper Sandusky	730*	730*	740	740
Tymochtee Creek	350	–	340	–
Unmeasured	1,200	1,550	1,190	1,540
Total (Upper Sandusky to Mexico)	2,280	2,280	2,270	2,280
Mexico*	2,270	2,270	2,270	2,270
Mexico	2,270*	2,270*	2,110	2,230
Honey Creek	450	–	450	–
Wolf Crek	1,060	–	1,040	–
Unmeasured	1,650	3,030	1,690	3,060
Total (Mexico to Fremont)	5,430	5,300	5,290	5,290
Fremont*	5,290	5,290	5,290	5,290

*Measured field data and used as input to the calculational procedure

Table 3 - Example of a Detailed Total Phosphorus Mass Balance
Storm of 77/02/22

Sources - From Bucyrus	Flow (millions)	Total Phosphorus (metric tons) (unmeasured inflow concentration 0.2 mg/l)
Bucyrus	321	6.22
Broken Sword Creek	268	2.21
Unmeasured	144	0.81
Net Resuspension/Deposition (Bucyrus to Upper Sandusky)	-	12.63
Total (Bucyrus to Upper Sandusky)	733	21.87
Upper Sandusky	740	22.09
Tymochtee Creek	340	3.03
Unmeasured	1,190	6.75
Net Resuspension/Deposition (Upper Sandusky to Mexico)	-	24.01
Total (Upper Sandusky to Mexico)	2,270	55.88
Mexico	2,110	54.78
Honey Creek	450	14.14
Wolf Creek	1,040	4.25
Unmeasured	1,690	9.56
Net Resuspension/Deposition (Mexico to Fremont)	-	17.24
Total (Mexico to Fremont) (for Fremont)	5,290	99.97

Table 4 - Example of a General Total Phosphorus Mass Balance
Storm of 22 February 1977

Sources - From Bucyrus to Fremont	Flow (millions cubic feet)	Total Phosphorus (metric tons) (unmeasured inflow concentration 0.2 mg/l)	Total Phosphorus (percentages)
Bucyrus	303	6.10	6.1
Broken Sword Creek	255	2.20	2.2
Tymochtee Creek	317	3.00	3.0
Honey Creek	450	4.30	4.3
Wolf Creek	1,040	14.10	14.1
Unmeasured	2,925	16.99	17.0
Net Resuspension/Deposition (Bucyrus to Fremont)	-	5.48	53.3
Fremont (total of the above)	5,290	99.97	100.0

the context of the above discussion of the discontinuities. The sources
traced in the model can be few or many depending upon the details desired and
the availability of the data. The corresponding budgets can be detailed or
general as desired. Table 4 shows a general total phosphorus budget where
the calculation discontinuities between reaches in Table 3 have been smoothed
out. Similar calculations could be performed for the parameters, e.g.
suspended sediment or chlorides, to get a suspended sediment or chloride
stream budget.

Management Implications

By applying the calculational procedure to various storms an engineer or
planner could develop land or stream management practices. The calculations
may be used to indicate a problem subbasin area which appears for all storms.
In the case of the Sandusky River as stated before, about half the measured
total phosphorus results from resuspension of bottom materials which origi-
nated from land runoff. Presumedly such material is carried with the sedi-
ment eroded from the land. Improvements in erosion control and changes in
land use will change the amount of material that shows up in the stream.
Immediate changes in water quality may be masked by the randomness of the
phenomenon that we are dealing with. True changes may not be evident for a
couple of years. Point source inputs tend to deposit during low flow pro-
viding a source of material for resuspension during high flows. In such
cases available phosphorus is "banked," transported by resuspension, and
delivered as potentially available total phosphorus. Besides controlling
sediment and phosphorus at its source on the land it may be possible to
control them in the stream by structural means. By using retention struc-
tures material could be forced to settle during low flows and retained there
during high flows, thus limiting the amount of input for resuspension.

CONCLUSION

The calculation of conservative substances (chloride and conductivity)
generally indicate the calculational procedure developed herein works well in
spite of the various approximations used. Using variable unmeasured inflow
concentrations during storms for conservative substances give good matches
for the measured and predicted values. Suspended sediment and total
phosphorus usually show resuspension for rising flows and deposition for
declining flows. This results in a net overall resuspension for the storm.
This withdrawal is balanced by a net deposition during low flow periods.
Resuspension of total phosphorus during storm events is shown downstream from
a phosphorus point source. Total phosphorus and other phosphorus are depo-
sited from the stream during low flow conditions and only total phosphorus is
removed from the sediments.

SUMMARY

A calculational technique has been presented for tracing the transport of
nutrients, suspended solids, and other chemical substances in a stream. At a
given point in a stream, these materials are derived from various upstream
sources. This procedure permits the calculation of the fractions of material

derived from these sources. Also the calculation of the amount of resuspension and deposition of total phosphorus and suspended solids in various stream reaches is possible.

Although the calculation of conservative substances indicates the method works fairly well in spite of the various approximations used, it must be remembered that this procedure was derived for the primary purpose of indicating what is happening at the downstream station of a reach during a storm event and not for the prediction of the chemistry along the reach.

It is also possible to develop total nutrient mass balances indicating contributions from various areas of the watershed.

This procedure was developed with the objective of providing insight as to what is happening to various sources of input materials with the least amount of input data required. It is hoped this technique will provide researchers with a method of evaluating instream processing of various materials from various watershed areas.

More details can be obtained by referencing references 5-12 and 15.

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